Energy

by Hannah Ritchie and Max Roser

First published in 2015; most recent substantial revision in July 2018. This article previously covered aspects of energy access, including access to electricity and per capita consumption; you now find this material in our entry on Energy Access.

Access to energy is a key pillar for human wellbeing, economic development and poverty alleviation. Ensuring everyone has sufficient access is an ongoing and pressing challenge for global development.

However, our energy systems also have important environmental impacts. Historical and current energy systems are dominated by fossil fuels (coal, oil and gas) which produce carbon dioxide (CO_2) and other greenhouse gases– the fundamental driver of global climate change. If we are to meet our global climate targets and avoid dangerous climate change, the world needs a significant and concerted transition in its energy sources.

Balancing the challenge between development and environment therefore provides us with an ultimate goal of ensuring everyone has access to enough sustainable energy to maintain a high standard of living.

In this entry we attempt to cover the fundamental pillars we need to understand global and regional energy systems: their evolution through time in terms of consumption, relative sources, and trade; progress in global energy access and our transition towards low-carbon sources; and crucially the main development, economic and health drivers behind the energy choices we make. It is intended to provide a fundamental background to the macro-trends in our historical and current energy systems, with key learnings on how we can use this understanding to shape pathways towards a sustainable future.

All our charts on Energy

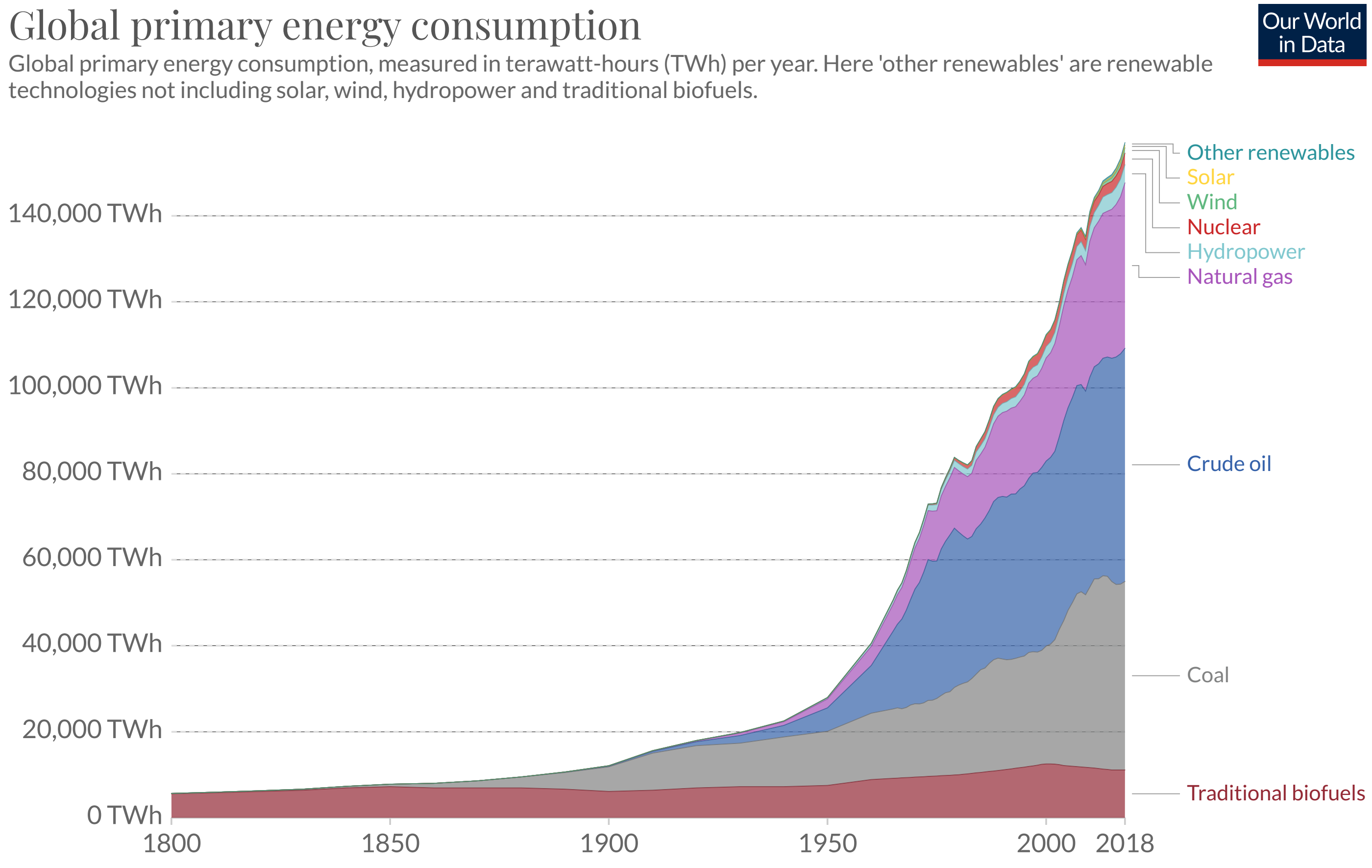
How much energy does the world

consume?

Let's first take a look at how global energy production- both in terms of quantity and source- have changed over the long-term. In the visualisation we have plotted global energy consumption from 1800 through to 2018. Note that you can use the absolute/relative toggle on the chart to view these in absolute numbers or as the percentage of the global total.

Global primary energy consumption

Global primary energy consumption, measured in terawatt-hours (TWh) per year. Here 'other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels.



Source: Vaclav Smil (2017) and BP Statistical Review of World Energy

Relative CHART DATA SOURCES

Energy production by region

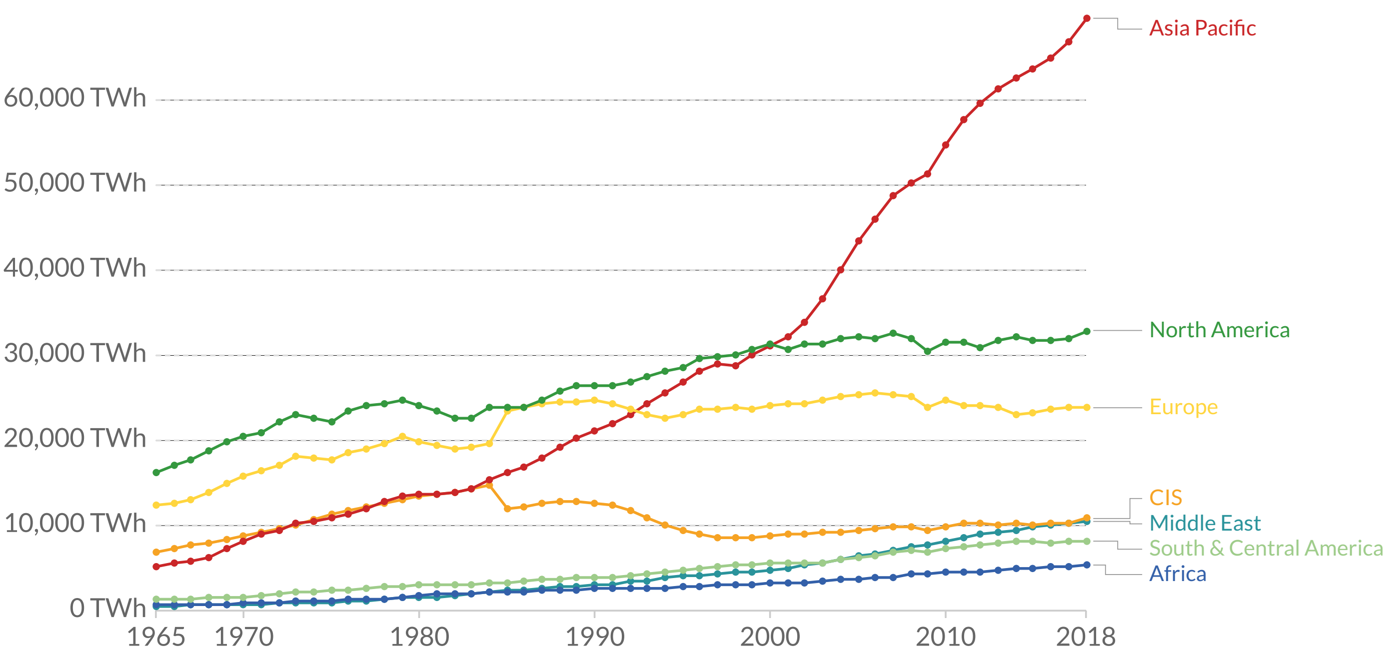
How are total levels of consumption distributed across the world's regions? In the chart we see primary energy consumption from 1965-2015 aggregated by continental regions. Note that this dataset only includes commercially-traded fuels (coal, oil and gas), nuclear, and modern renewables. This means traditional biofuels are not included; as a result, figures are likely to be a small underestimate for regions (predominantly Africa and developing Asia) where populations still strongly rely on traditional biomass as a primary fuel source.

In 1965 the bulk of total energy was consumed North America, Europe and Eurasia- collectively, they accounted for more than 80 percent of global energy consumption. Although energy consumption has increased in these regions since the 1960s, their relative share of the total has declined significantly. Consumption across the rest of the world has been increasing, most dramatically in the Asia Pacific where the total consumption increased more than 12-fold over this period.

As a result, in 2015 Asia Pacific was by far the largest regional consumer with 42 percent- this was about the same as North America, Europe and Eurasia combined (at 43 percent). The Middle East, Latin America and Africa account for around seven, five and three percent, respectively.

Primary energy consumption by world region, 1965 to 2018

Primary energy consumption is measured in terawatt-hours (TWh). Note that this data includes only commercially-traded fuels (coal, oil, gas), nuclear and modern renewables used in electricity production. As such, it does not include traditional biomass sources.



Source: BP Statistical Review of World Energy (2019)

1965 2018

Relative change CHART DATA SOURCES

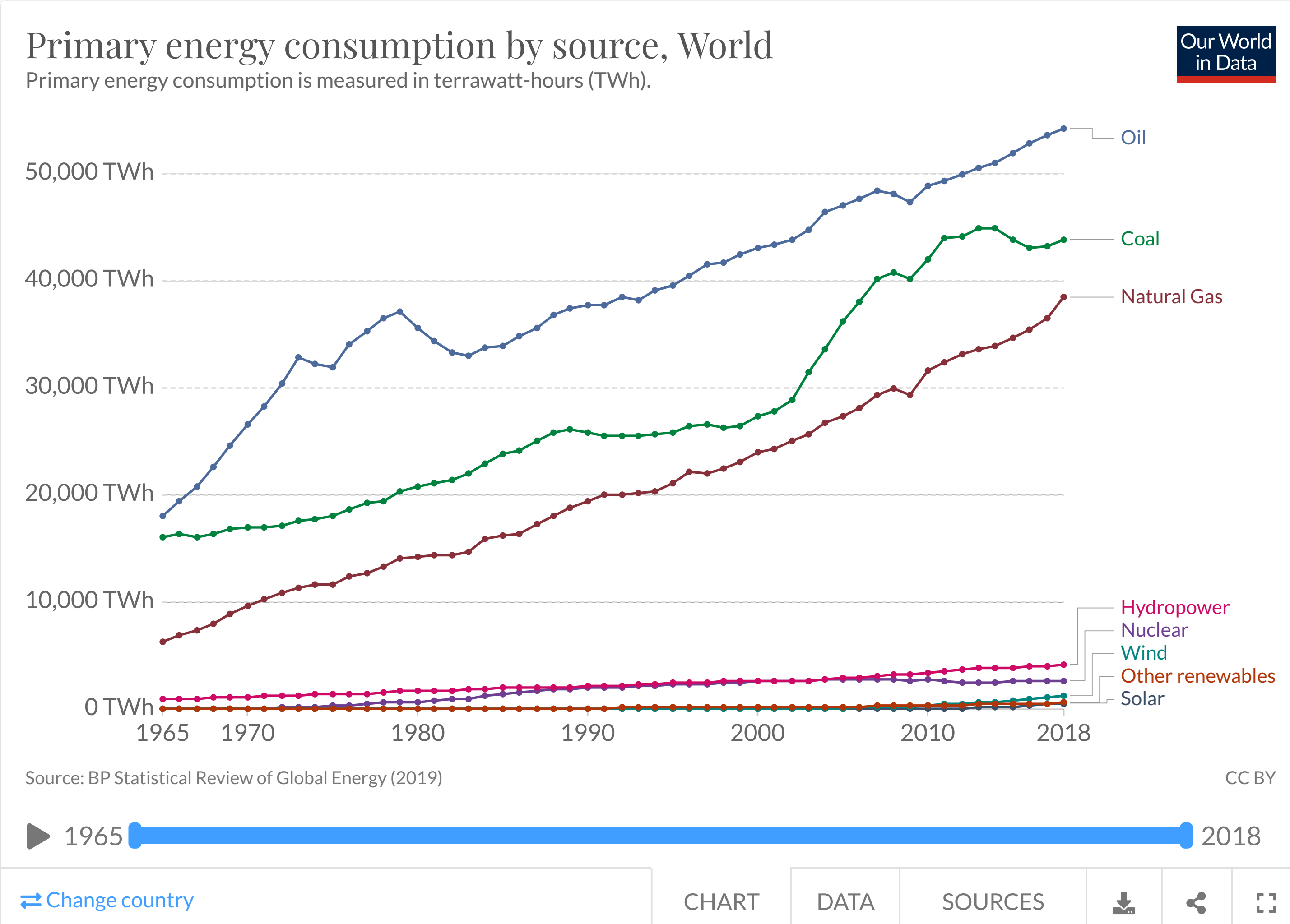
Energy consumption by source

In the visualizations we compare the breakdown of energy consumption by source.

This can be shown in two ways – as 'primary' energy consumption, and as energy consumption 'corrected' for inefficiencies in fossil fuel conversions.

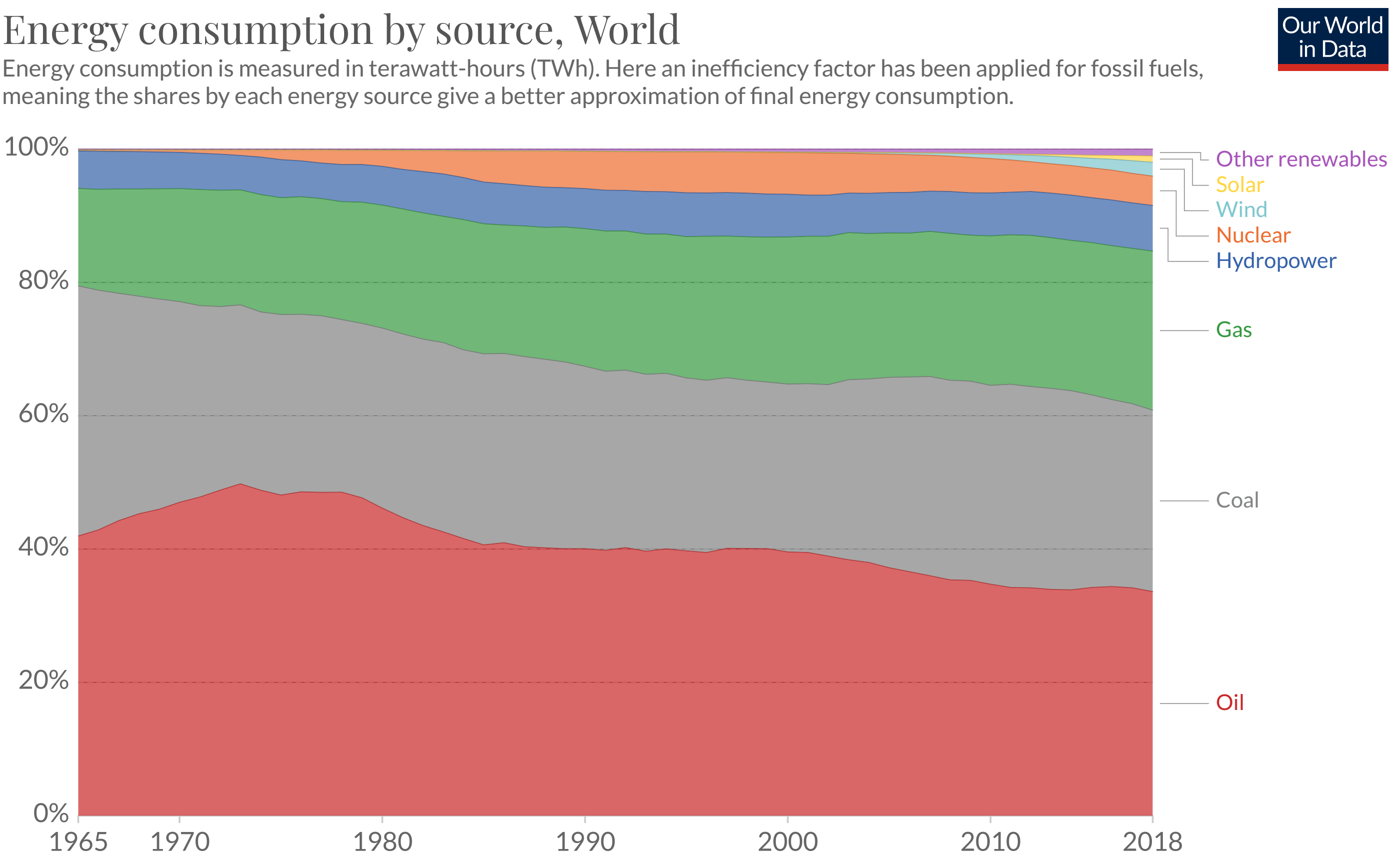
Primary energy consumption is often called the 'direct method' as it shows energy statistics exactly in their raw form: how much coal, oil and gas energy are consumed as inputs to the energy system.

But, this approach does not account for the inefficiencies that fossil fuels incur when converted into final energy. We therefore show values corrected by what is termed the 'substitution method' – this gives a better approximation of final energy demand, and is often viewed as a more appropriate way to compare the shares of different energy sources.



Energy consumption by source, World

Energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.



Source: BP Statistical Review of World Energy (2019)
Note: 'Other renewables' includes geothermal, biomass and waste energy.

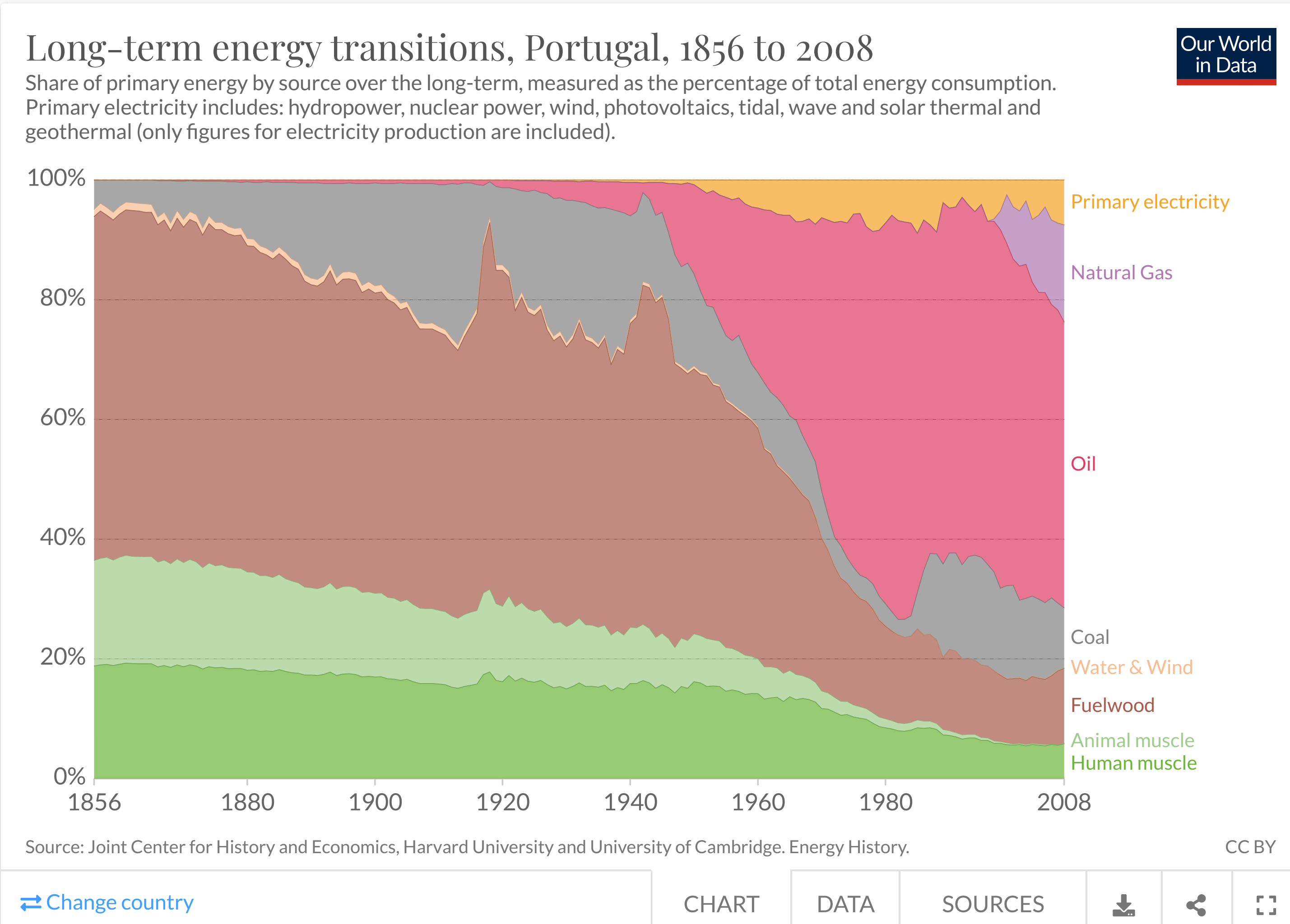
Change region | CHART | DATA | SOURCES

Long-run energy transitions in countries

While most people associate the advent of energy with the uptake of coal, it's important to understand what modern fuels have replaced by taking a long-term perspective on the evolution of human energy systems. In the chart we see long-term trends in energy transitions in Italy; this figure has been developed based on data from Gales et al. (2007).[1]

Similar data across a range of countries in Europe and the Americas has been made available at the Energy History project at the Joint Center for History and Economics, Harvard University and University of Cambridge you can explore these trends using the "change country" function in the chart.

These trends provide an additional energy dimension: human and animal power. The inclusion of muscle, food for labour and animal feed reminds us of the important earlier transition in these economies from human and animal labour to industrialised energy production. In high-income countries, the uptake of fossil fuels- and later, the integration of renewable and nuclear technologies- has effectively eliminated the use of human or animal labour. In some low-to-middle income nations, the contribution of a human labour force (especially in agricultural and manufacturing sectors) is still significant, but continuing to progress through the composition shifts we see in the figures.



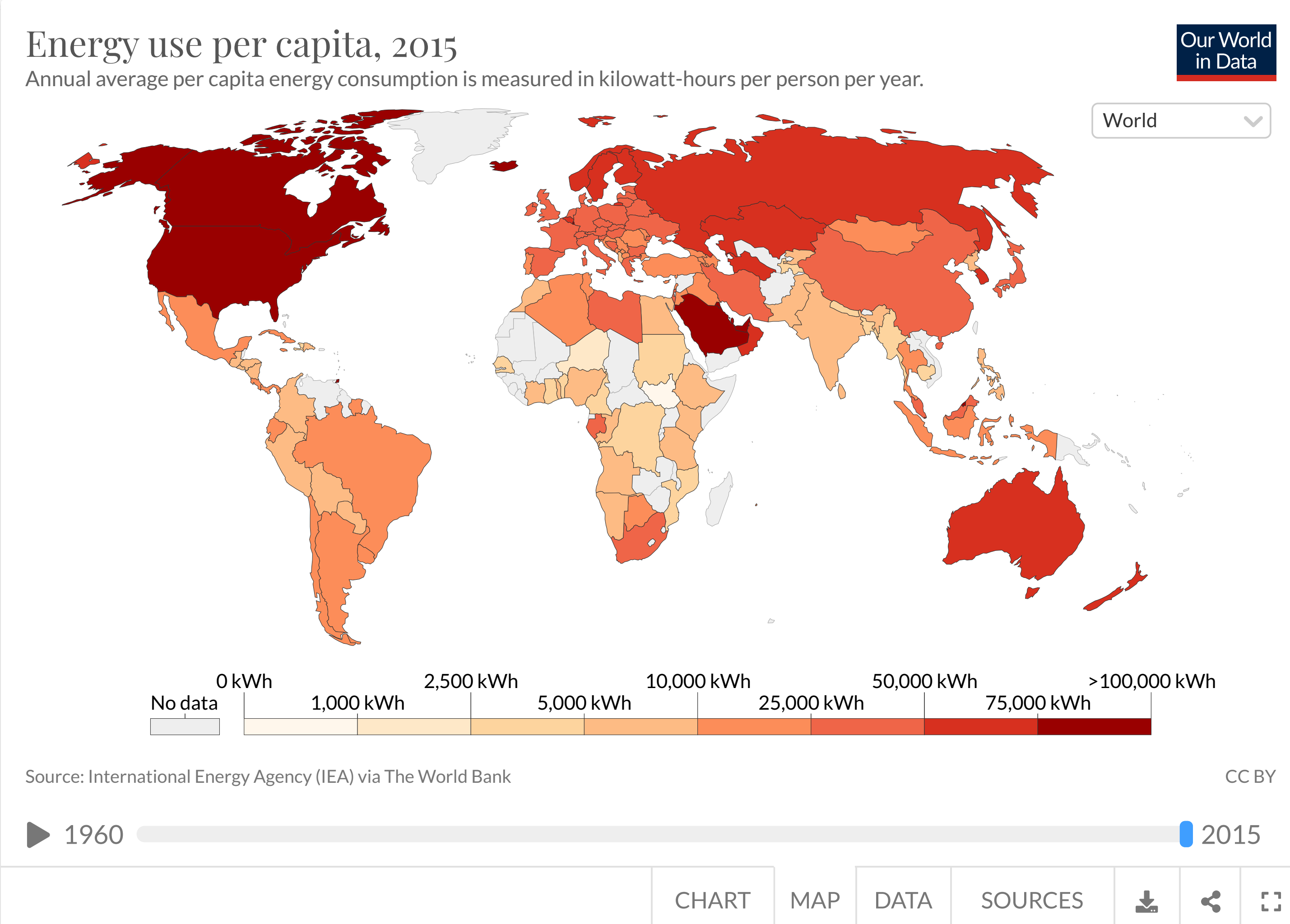
Per capita energy consumption

Here we see trends in per capita energy use from 1960-2014; this is inclusive of all dimensions of energy (electricity plus transport and heating), not exclusively electricity (with energy normalised kilowatt-hour equivalents per year). There are several important points to note. Firstly, global average per capita energy consumption has been consistently increasing; between 1970-2014, average consumption has increased by approximately 45 percent.

This growth in per capita energy consumption does, however, vary significantly between countries and regions. Most of the growth in per capita energy consumption over the last few decades has been driven by increased consumption in transitioning middle-income (and to a lesser extent, low income countries). In the chart we see a significant increase in consumption in transitioning BRICS economies (China, India and Brazil in particular); China's per capita use has grown by nearly 250 percent since 2000; India by more than 50 percent; and Brazil by 38 percent.

Whilst global energy growth is growing from developing economies, the trend for many high-income nations is a notable decline. As we see in exemplar trends from the UK and US, the growth we are currently seeing in transitioning economies ended for many high-income nations by over the 1970-80s period. Both the US and UK peaked in terms of per capita energy consumption in the 1970s, plateauing for several decades until the early 2000s. Since then, we see a reduction in consumption; since 2000, UK usage has decreased by 20-25 percent.

Nonetheless, despite this decline in high-income countries, large global inequalities still exist. The average US citizen still consumes more than ten times the energy of the average Indian, 4-5 times that of a Brazilian, and three times more than China. The gulf between these and very low-income nations is even greater- a number of low-income nations consume less than 500 kilograms of oil equivalent per person.



Energy intensity of economies

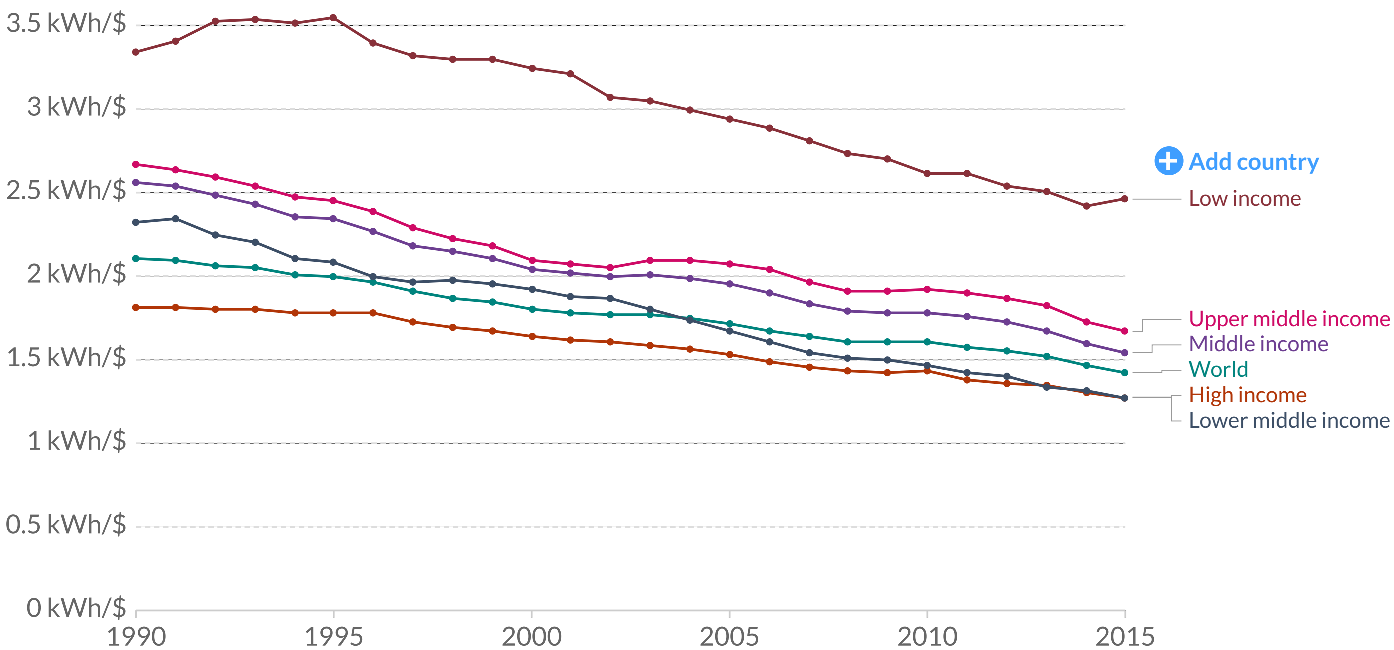
If we want to continue growing economically, increasing prosperity, and working towards poverty elimination (which most countries and individuals do) whilst efficiently managing energy resources (and reducing greenhouse gas emissions), 'energy intensity' becomes an important metric for tracking progress. Energy intensity measures the quantity of energy needed to produce one unit of gross domestic product (GDP) growth. It's typically measured in kilowatt-hours of energy needed to produce one dollar of growth (kWh per dollar). It is essentially a measure of the energy efficiency of economies; we want to achieve economic growth with as low an energy input as possible.

In the chart we show how the energy intensity of economies have changed since 1990 (measured in kWh per 2011 international-$). Here, we see a distinct downward trend- at the global level, as well as across all income-level brackets. Note that you can view trends for individual countries on the interactive chart, and get a global overview using the 'map' tab.

In 1990, as a global average, it took 2.1 kWh of energy to produce one international dollar of economic output; in 2014 this had declined to 1.5kWh. This represents a 30 percent reduction. Efficiency gains have been seen across all income-levels. High-income economies typically have the lowest energy-intensity (i.e. they are more energy efficient per unit of economic output), and a large efficiency gap exists between lowest-income nations and the rest of the world. The relative energy intensity of economies is strongly linked to their composition, and more specifically the share of services versus industry and manufacturing output. The links between energy intensity and economy composition are discussed later in this entry.

Energy intensity of economies, 1990 to 2015

Energy intensity level of primary energy is the ratio between energy supply and gross domestic product measured at purchasing power parity. Energy intensity is an indication of how much energy is used to produce one unit of economic output. Lower ratio indicates that less energy is used to produce one unit of output.



Source: World Bank, Sustainable Energy for All (SE4ALL)

1990 2015

CHART MAP DATA SOURCES

Are we making progress on decarbonization?

If we want to reduce our global greenhouse gas emissions, the world has to transition from an energy system dominated by fossil fuels to a low-carbon one (this is what most countries have set long-term targets to achieve within the Paris climate agreement).[2]

With the exception of carbon capture and storage (CCS) technology (described later in the entry), we have two options to achieve this: renewable technologies (including bioenergy, hydropower, solar, wind, geothermal, and marine energy) and nuclear energy. Both of these options produce very low CO_2 emissions per unit of energy compared with fossil fuels. We call this process of transitioning from fossil fuels to low-carbon energy sources 'decarbonisation'.

In the first section of this entry, we saw that our progress in decarbonising our total energy system (including transport, heat and electricity) has been slow. Fossil fuels are still the dominant energy source. If we focus on our electricity sector in particular, are we performing any better?[3]

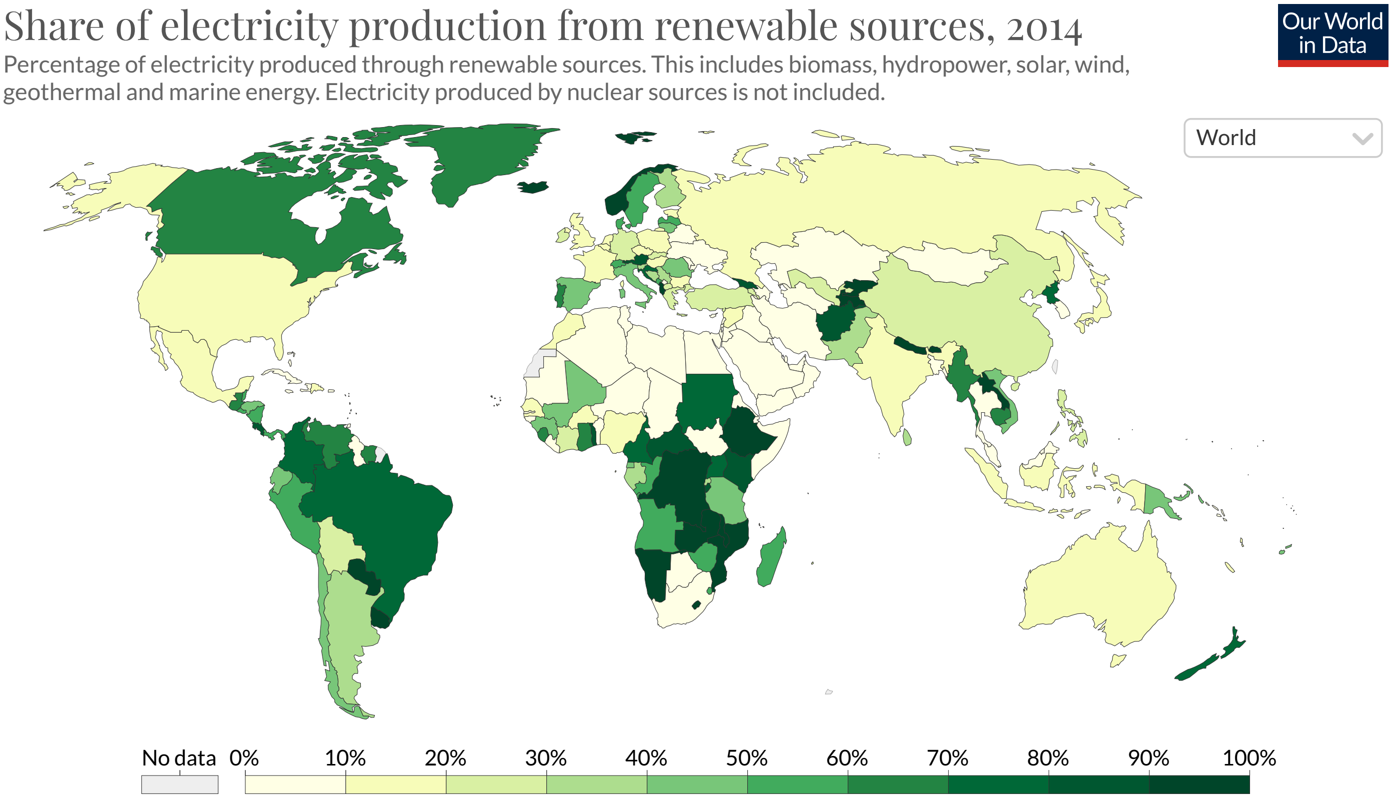
Our progress over the last decade tells an interesting story which we have covered in its own blog post. These trends can be explained in the four charts which map the share of renewable, nuclear and fossil fuel sources in global electricity production. As a brief summary: over the last decade (2005-2015) the share of renewables in our electricity mix has increased by approximately 5-6 percent. This is good news. However, over this same period, the share from nuclear production has decreased by almost exactly the same amount (5-6 percent).

Overall, this means that our total share of low-carbon electricity production is almost exactly the same as a decade ago (as shown in the chart). In fact, if we compare the share of electricity produced by low-carbon sources (renewables and nuclear) in 2015 to that of 1990 , we see that it has dropped by around three percent. Progress on electricity decarbonisation has been stalled over the last decade as a result of a growing aversion to nuclear energy.

The final chart provides a breakdown of fossil fuel sources in our electricity mix. Since 2005, natural gas and coal have increased their share by one and two percent, respectively whereas the contribution from oil has declined by two percent. Nonetheless, overall, the relative mix of electricity sources has changed very little over the last few decades.

Share of electricity production from renewable sources, 2014

Percentage of electricity produced through renewable sources. This includes biomass, hydropower, solar, wind, geothermal and marine energy. Electricity produced by nuclear sources is not included.

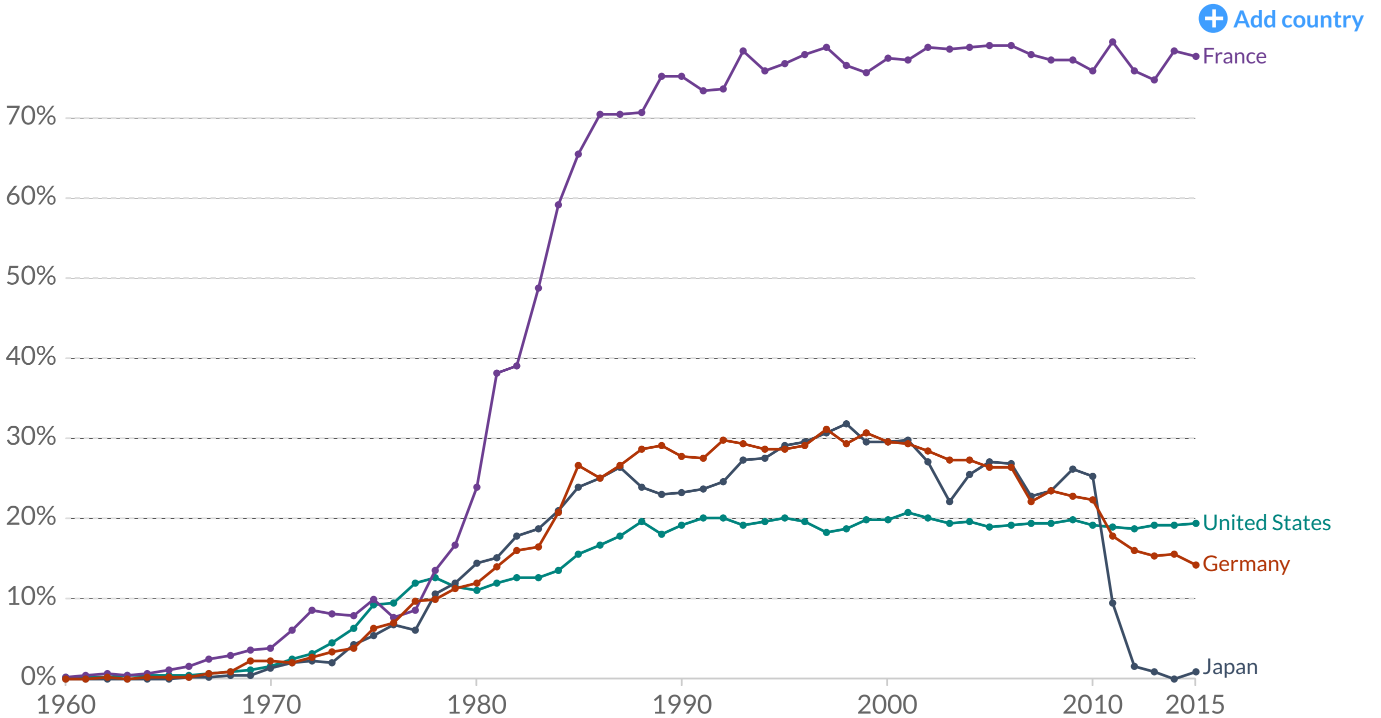


Source: World Bank, Sustainable Energy for All (SE4ALL)

1990 2014

CHART MAP DATA SOURCES

Share of electricity production from nuclear



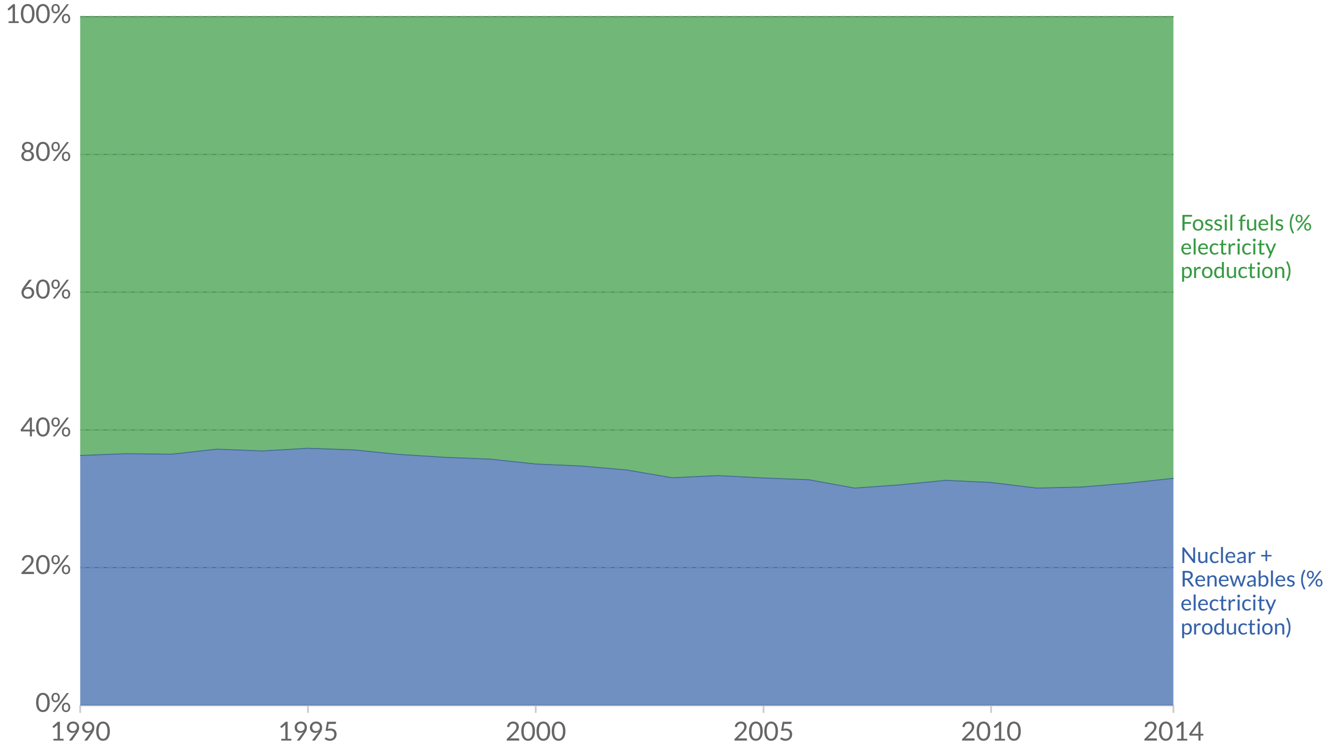
Source: International Energy Agency (IEA) via The World Bank

1960 2015

CHART MAP DATA SOURCES

Global electricity production by source

Global electricity production, measured as the percentage contribution from fossil fuels (coal, oil and gas) and low-carbon sources (nuclear, hydropower, biomass, wind, solar, geothermal and marine power)

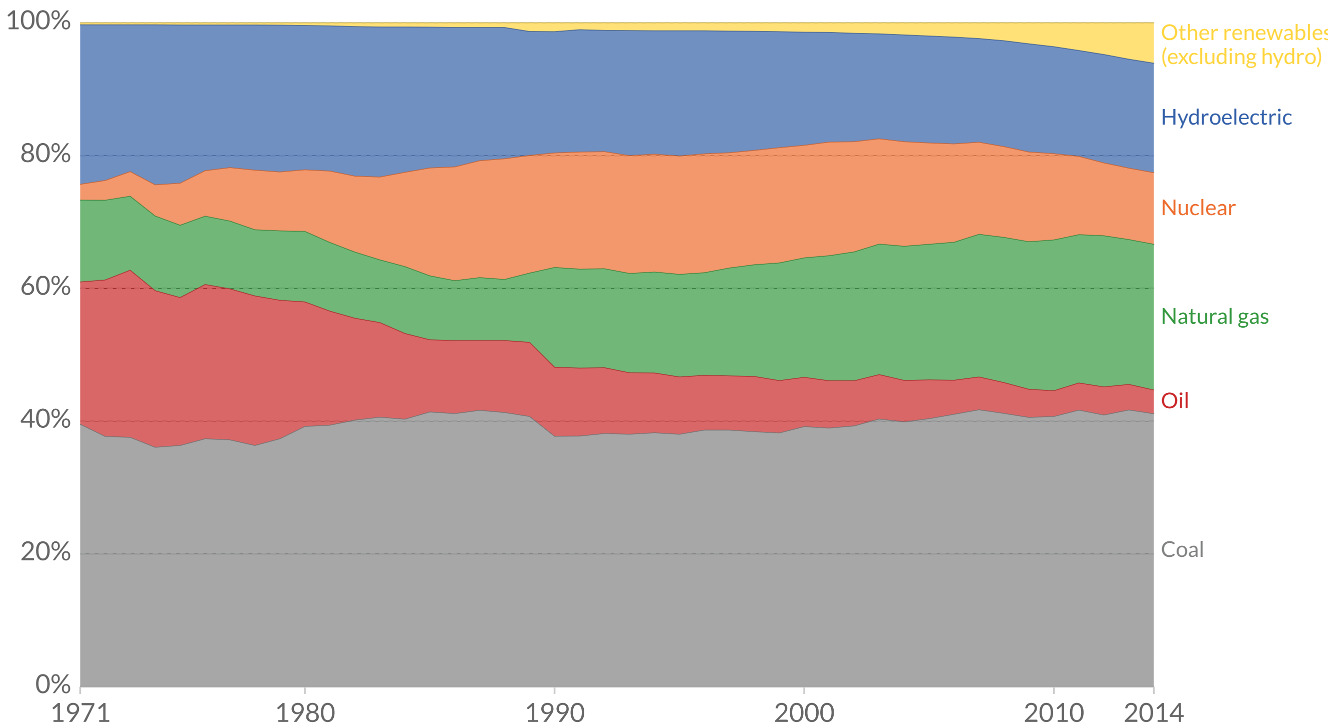


Source: International Energy Agency (IEA) via The World Bank

CHART DATA SOURCES

Electricity share by fuel source, World, 1971 to 2015

Electricity production (measured as the percentage of total electricity production) by source (coal, oil, gas, nuclear, hydroelectric power and other renewables). Other renewables in this definition includes biomass, wind, solar, geothermal, and marine power.



Source: International Energy Agency (IEA) via The World Bank

Change CHART DATA SOURCES

Global energy trade

The distribution of energy resources can have an obvious impact on energy trade across the world. The other important factor in energy trade is domestic levels of energy consumption. If you are a country rich in resources but also have high domestic levels of consumption, you may have little energy left to export. Similarly, if a country has low levels of energy consumption, if may still be a net exporter of energy despite have comparatively low levels of natural resources. Other influences on energy trade may be geopolitical: for example, some countries may want to converse fuel resources to maintain levels of energy security into the future.

In the two charts we have graphed energy imports and exports, both by income level and by region. Note that you can also manually select countries to compare. Here we have measured energy imports and exports as a percentage of domestic energy use, where a positive percentage indicates a country or region is a net *importer* of energy, and negative is a net *exporter*. For example, collectively high-income nations in 2014 imported nearly five percent of consumed energy.

In terms of income level, we see that there is a distinct flow of energy resources from low, middle and upper middle income to high-income nations (with the exception of lower middle income). On a continental basis, we see the dominance of energy exports from the Middle East & North Africa (being a net exporter of 127 percent of its consumption levels). Interestingly, Sub-Saharan Africa is also a net exporter of energy (despite having low levels of coal reserves and only moderate levels of oil and gas)- this is most likely a result of low levels of domestic consumption. North America and Europe & Central Asia reach approximately energy parity (effectively balancing consumption with trade). South Asia is a net importer of energy, importing approximately one-third of its energy consumption.

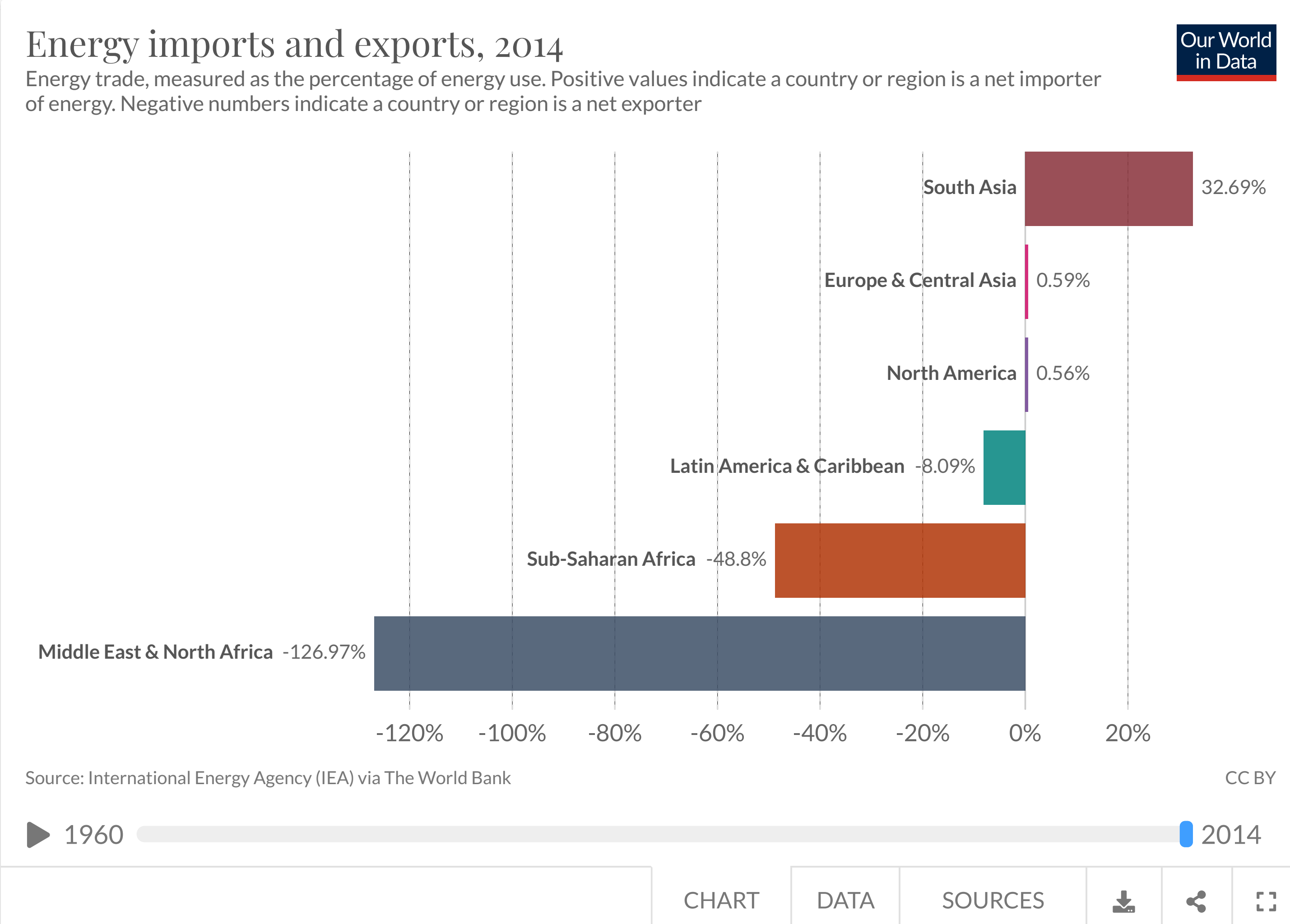
Energy imports and exports, 2014

Energy trade, measured as the percentage of energy use. Positive values indicate a country or region is a net importer of energy. Negative numbers indicate a country or region is a net exporter

Source: International Energy Agency (IEA) via The World Bank

1960 2014

CHART DATA SOURCES



Investment in renewable technologies

Shifting our energy systems away from fossil fuels towards renewable technologies will require significant financial investment. But how much are we really investing in the sector, and how is this finance distributed across the world?

In the graph we see global investments in renewable technologies from 2004 to 2015 (measured in billion USD per year). In 2004, the world invested 47 billion USD. By 2015, this had increased to 286 billion USD, an increase of more than 600 percent. Investment has grown across all regions, but at significantly different rates. Note that you can use the 'absolute/relative' toggle on the chart to compare regions on relative terms. Growth has been greatest in China, increasing from 3 billion USD in 2004 to 103 billion USD by 2015 (an increase of 3400%). China is now the largest single investor in renewable technologies, investing approximately the same as the United States, Europe and India combined.

Combining Chinese and Indian investment with its neighbours, Asia & Oceania is the largest continental investor. Europe's investment has been through a significant growth-peak-reduction trend, peaking in 2011 at 123 billion USD before declining to 49 billion USD in 2015. Investment in the Middle East & Africa remains relatively small, but has shown significant growth over the last ten years (after investing only 0.5 billion USD in 2004).

Levels of absolute investment tell an important story, but are disadvantaged by the fact that they take no account of the size of investments relative to a country's economy. We might expect that the largest economies would also be the largest investors. If we want to assess which countries are making a fair 'contribution' or 'share' to investment in clean energy, it is useful to assess investment contributions as a percentage of a country's gross domestic product (GDP). We have calculated this (as a percentage of GDP) and plotted it for the largest single-country investors in one of the charts.

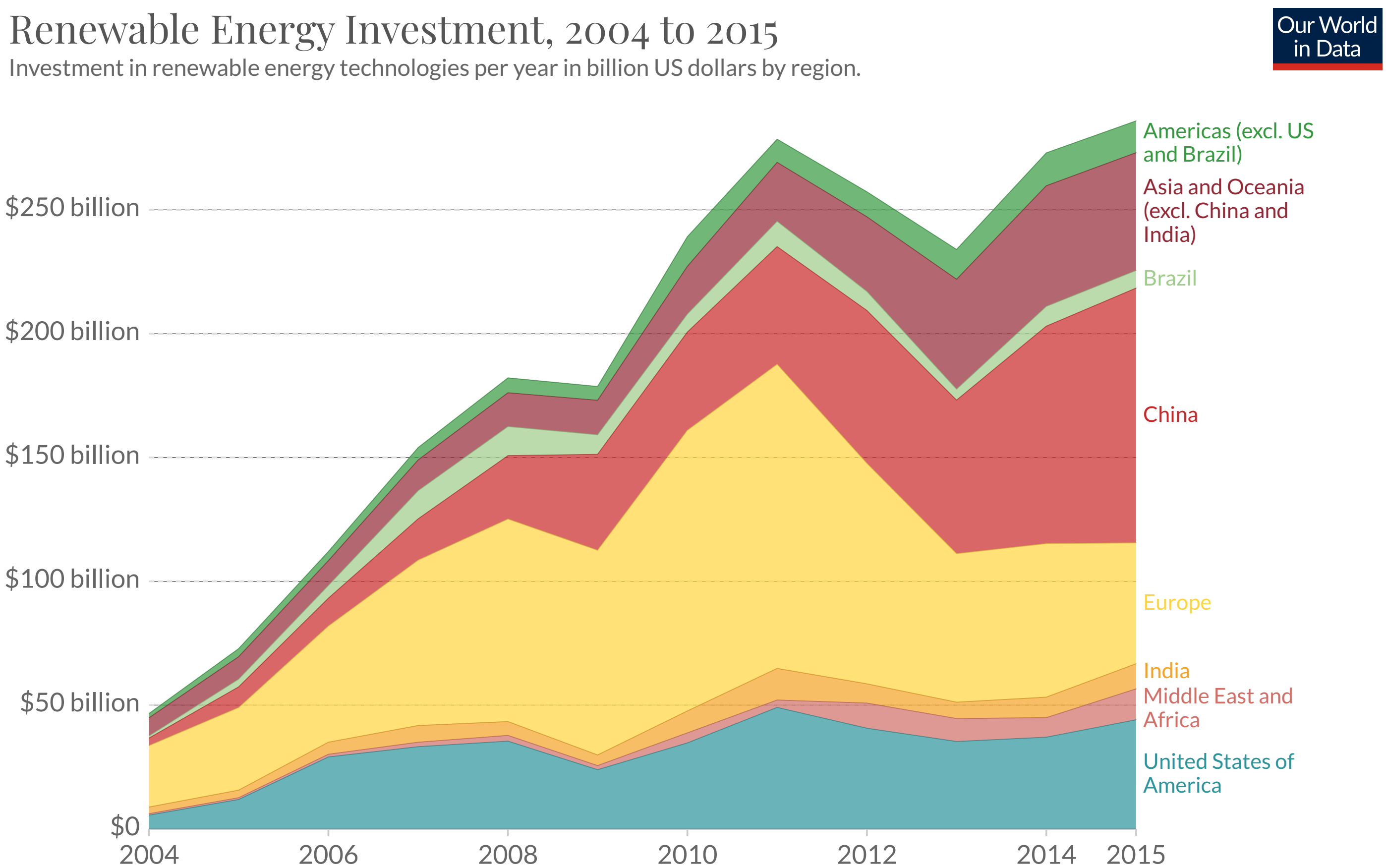
This tells a slightly different story. Most countries invest less than one percent of GDP in renewable technologies (with the exception of South Africa and Chile, which make an impressive contribution at 1.4 percent). When normalised to GDP, China remains one of the largest investors, at 0.9 percent. Interestingly, despite being the second largest investor in absolute terms, the United States invested only 0.1 percent of its GDP in 2015.

Indeed, when it comes to relative contributors to renewable energy, low-to-middle income transitioning economies typically invest more than high-income nations. This may be partly explained by the fact that these nations are likely to be investing a higher percentage of their GDP into energy provision and expansion overall (whereas high-income nations typically have well-established energy systems). Nonetheless, most high-income nations have set ambitious greenhouse gas reduction targets in their commitments to the Paris climate agreement.[4]

Achieving these targets will require significant investments in low-carbon technologies.

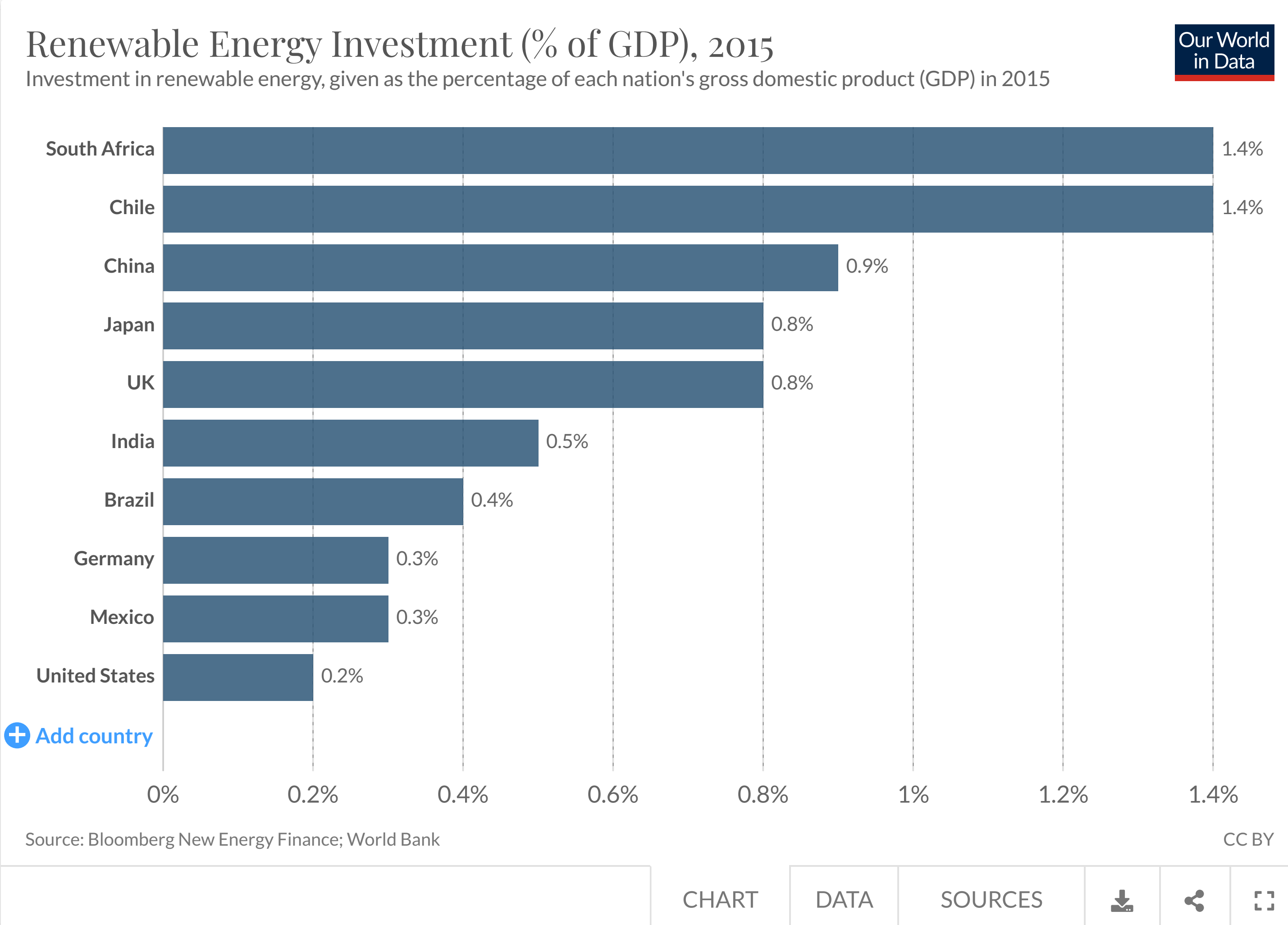
Renewable Energy Investment, 2004 to 2015

Investment in renewable energy technologies per year in billion US dollars by region.



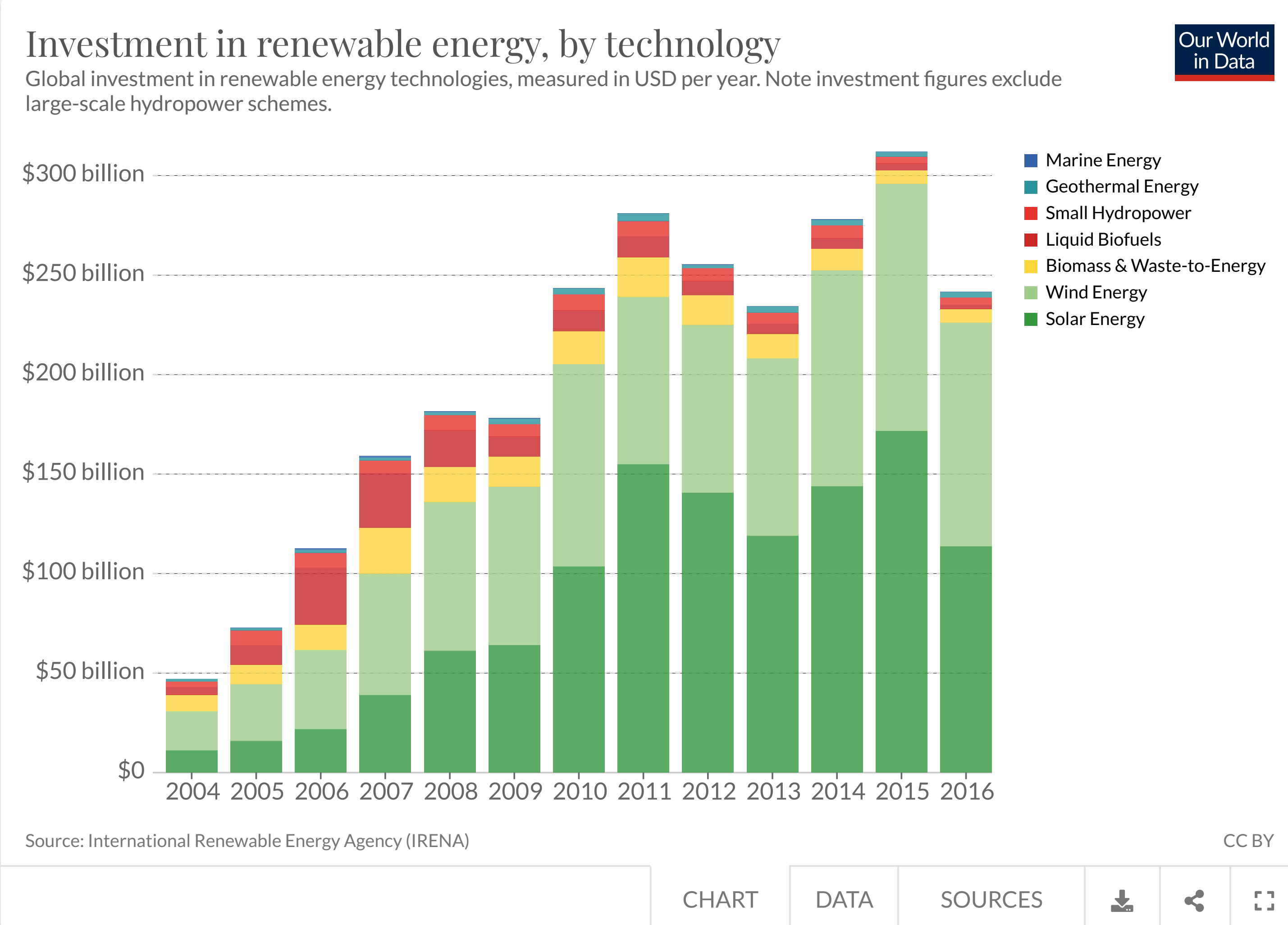
Source: International Renewable Energy Agency, 2017

Relative CHART DATA SOURCES



We have looked at investment trends by region, but which renewable technologies are receiving the largest investment? In the chart we have shown global investment trends by energy source, through to 2016. Note that large hydropower is not included in these figures. Again, you can switch between the 'absolute/relative' toggle to see comparisons in each.

In 2016, solar and wind energy both received 47 percent of investment (combining to account for 94 percent of global finance). These two technologies have been taking an increasing share, especially over the last five years. In 2006, bioenergy (both in the form of biomass and liquid biofuels) took a sizable share of global investment, peaking at 36 percent. This has dwindled over the last decade, receiving less than four percent in 2016. These trends suggest that investors see solar and wind energy as the dominant renewable technologies of the future.



What drives energy consumption?

IN THIS SECTION

Energy use is strongly related to economic growth and poverty allevation

Energy has a crucial role to play in a global development context. The potential for energy to improve living standards, whether through the freeing of time from household chores (for example, washing clothes or cooking); increased productivity; improved healthcare and education services; or digital connections to local, regional and global networks.

The link between energy consumption and economic growth has been a topic of wide discussion. A large number of studies have attempted to derive the causal relationship between energy consumption and economic growth, however no clear consensus has emerged.[5]

This can be partly attributed to the fact that the link between energy and prosperity is not always unidirectional. Gaining access to electricity and other energy sources may provide an initial increase in GDP, but having higher GDP may in turn drive higher energy consumption. Additionally, progress in development outcomes can be complex: a number of parameters may be improving at the same time. If, for example, energy access and consumption, nutrition, education, health, and sanitation are all improving simultaneously (and having complex relationships with one another), it can be hard to directly attribute improvement in living standards back to a single parameter.

Chontanawat et al. (2008) carried out a systematic study across 100 countries to try to reach a common consensus on the energy-GDP link.[6]

Akinlo (2008) did similarly across 11 Sub-Sahara African countries to define a common relationship.[7]

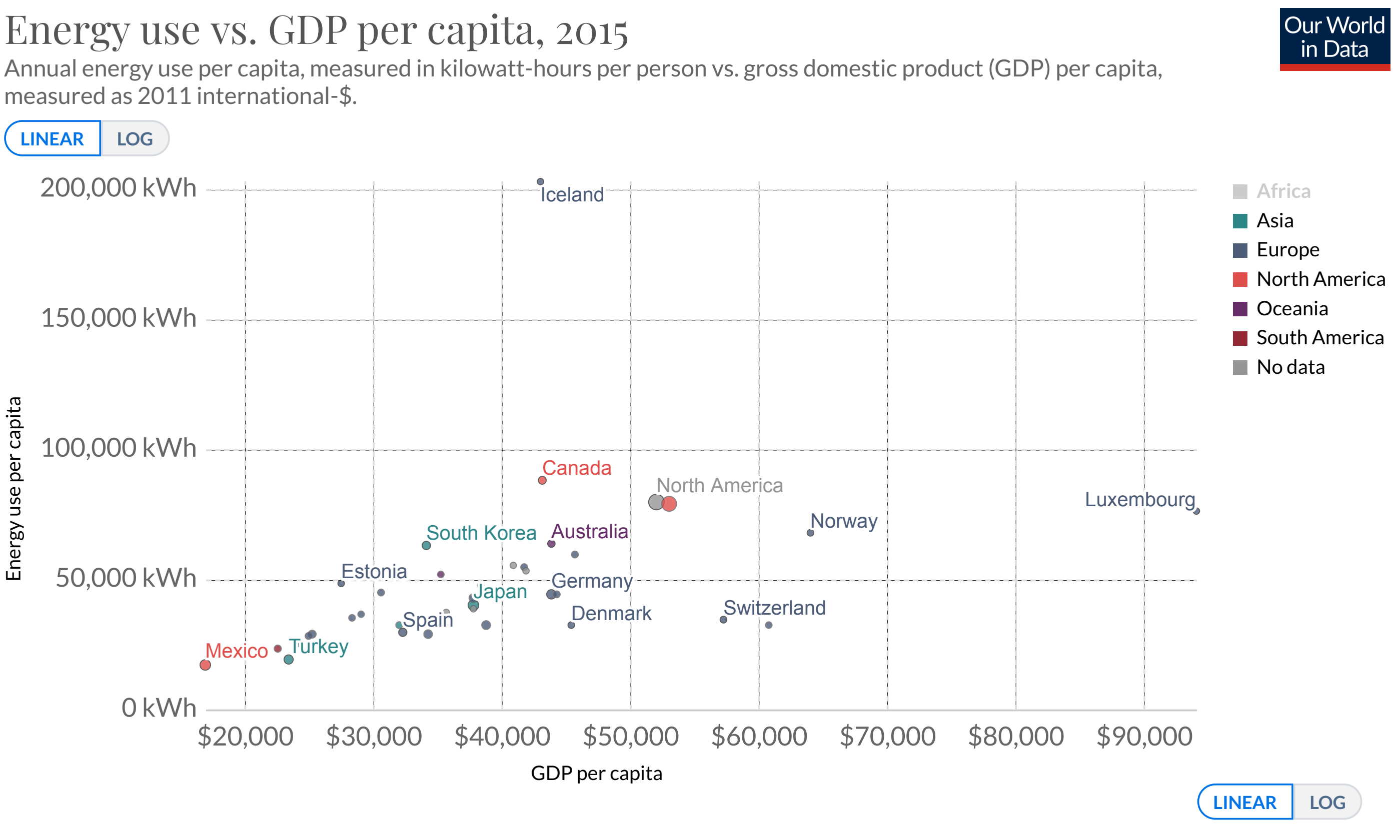
Neither found a causal relationship which was true in all contexts. For some countries, the relationship was unidirectonal (energy consumption was a direct and long-term driver of economic growth), others are bidirectional; some are cointegrated with other factors; and for some there was actually no clear link between the two. Nonetheless, for most countries, there is an important relationship between energy and prosperity. However, the exact dynamics of each is complex and context-dependent.

What does our data suggest of this link between the two? In the chart we have plotted per capita energy consumption (on the y-axis) versus per capita GDP (PPP-adjusted) (on the x-axis) for the year 2015. Indeed, we see a strong trend: typically the higher a country's average income, the more energy it consumes. In our second chart we present the percentage of the population with access to electricity (y-axis) versus GDP per capita (x-axis). If we press play and watch how these trends evolve through time, we see a similar trend: both electricity access and prosperity increase for most countries through time. However, in both of these visualisations, it's challenging to differentiate how much of this trend can be explained by energy-led growth, and how much is a result of growth-led energy consumption.

In our final chart we have plotted the relationship between per capita energy consumption (y-axis) and the share of the population in extreme poverty (x-axis). In general, we see a trend of poverty alleviation with higher energy consumption levels. However, this does not necessarily hold as a direct relationship for all countries.

Energy use vs. GDP per capita, 2015

Annual energy use per capita, measured in kilowatt-hours per person vs. gross domestic product (GDP) per capita, measured as 2011 international-$.



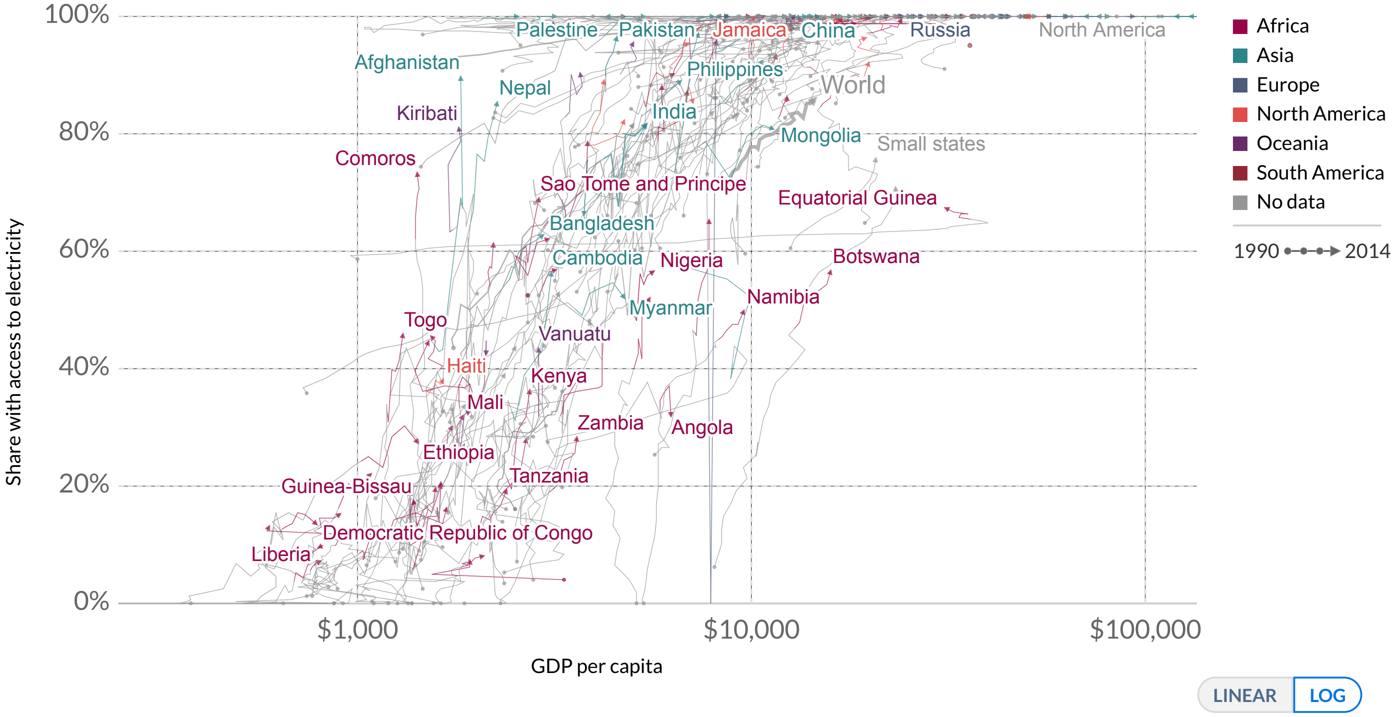
Source: International Energy Agency (IEA) via The World Bank

1990 2015

Select countries Average annual change CHART DATA SOURCES

Access to electricity vs. GDP per capita, 1990 to 2014

GDP per capita is adjusted for price differences between countries and inflation and measured in international-$.



Source: The World Bank - World Development Indicators (WDI)

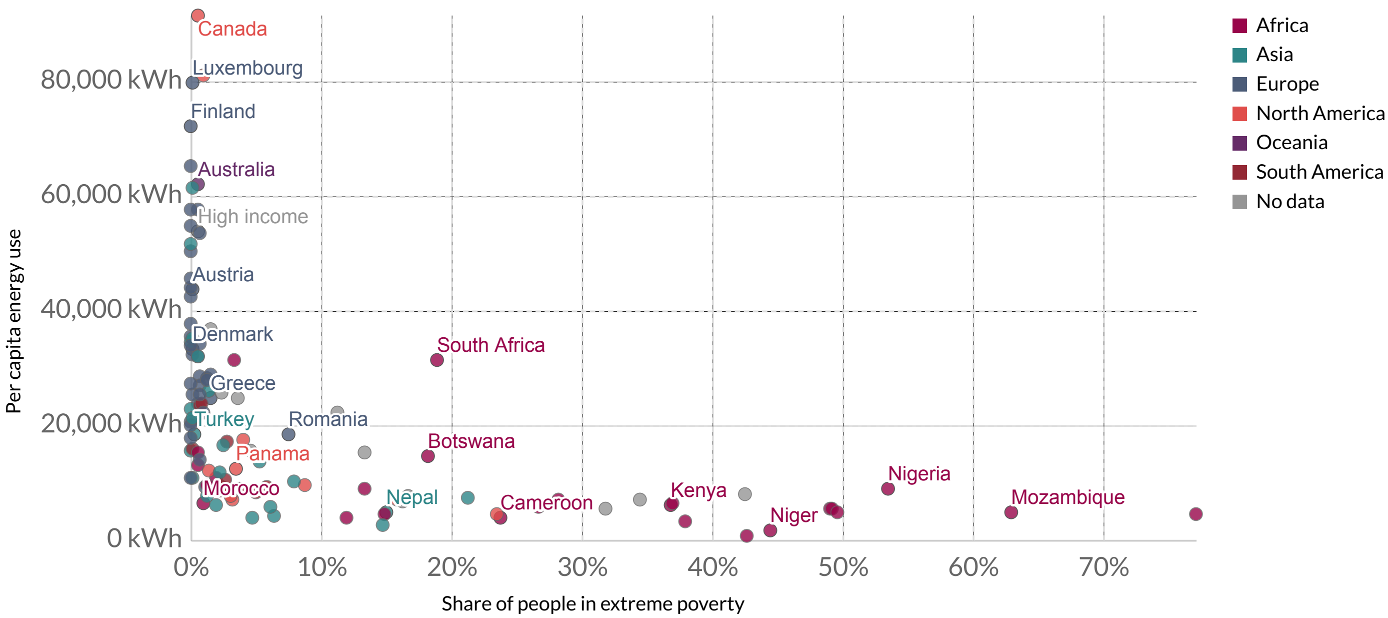
1990 2016

Select countries Average annual change CHART DATA SOURCES

Energy use per capita vs. share of population in extreme poverty, 2014

Per capita energy use is measured in kilowatt-hours (kWh) per year. Extreme poverty is defined as living at a consumption (or income) level below 1.90 "international-$" per day. International $ are adjusted for price differences between countries and price changes over time (inflation).

LINEAR LOG



Source: International Energy Agency (IEA) via The World Bank

1977 2015

Select countries Average annual change CHART DATA SOURCES

What drives choices of energy sources?

IN THIS SECTION

Relative cost of energy sources

Prices can strongly influence our choice of energy sources. In this regard, it is the *relative* cost between sources which is important. This is true in higher-income countries (we want low energy bills), but is increasingly important in low and middle-income economies. For many countries, increasing the share of the population with access to electricity and energy resources is a key priority, and to do so, low-cost energy is essential.

How do we compare the relative cost of energy? The dominant energy source in the transport sector is liquid fuels (diesel and gasoline) for which relative costs are less important than changes in price through time. Let's therefore focus on the relative costs of energy sources in the electricity sector.

To do this, we compare costs based on what we call the 'levelised cost of electricity' (LCOE). The LCOE attempts to provide a consistent comparison of electricity costs across sources but taking the full life-cycle costs into account. It is calculated by dividing the average total cost to build then operate (i.e. both capital and operating costs) an energy asset (for example a coal-fired power station, a wind farm, or solar panel) by the total energy output of that asset over its lifetime. This gives us a measure of the average total cost per unit of electricity produced. Measuring sources on this consistent basis attempts to account for the fact that resources vary in terms of their capital and operating costs (for example, solar PV may have higher capital costs, but lower operating costs relative to coal over time). Note that this cost of energy production has an obvious impact on electricity prices for the consumer: the LCOE represents the minimum cost producers would have to charge consumers in order to break-even over the lifetime of the energy project.

To be truly competitive, renewable technologies will have to be cost-competitive with fossil fuel sources. In the chart, sourced from IRENA's latest Rethinking Energy report, we see the LCOE (measured in 2016 USD per megawatt-hour of electricity produced) across the range of renewable technologies in 2010, and in 2016.[8]

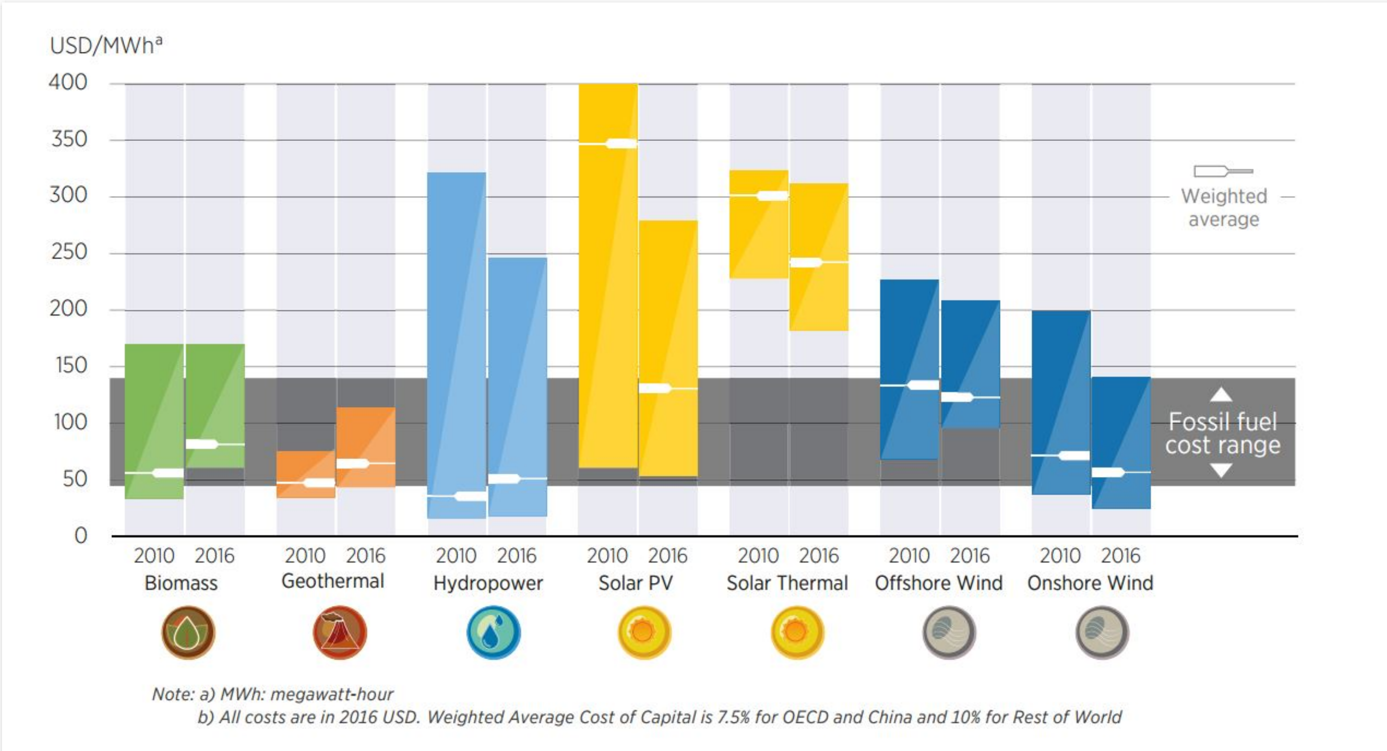
It's important to acknowledge that the relative costs of energy are context-dependent and vary across the world. For example, the relative cost of solar PV is likely to be lower in lower latitude countries than at high-latitudes because they will produce more energy of their lifetime. This can produce very different LCOE figures by region (and indeed the country-specific LCOE charts can vary significantly). For our global chart, this range of costs is represented as vertical bars for each technology. The white line in each represents the global weighted average cost per technology.

Similarly, the cost of fossil fuels can very depending on the fuel quality, ease of extraction and regional resources. The average range of fossil fuel costs is shown as the grey horizontal block.

What we see is that in terms of the 2016 weighted average cost, most renewable technologies are within a competitive range of fossil fuels. The key exception to this is solar thermal which remains about twice as expensive (although is falling). Hydropower, with the exception of traditional biomass, is our oldest and well-established renewable source: this is reflected in its low price (which can undercut even the cheapest fossil fuel sources). Note however that although the weighted average of most sources is competitive with the average fossil fuel cost, the wide range of potential costs means that this is not true for all countries. This is why the selection of particular technologies need to be considered on a local, context-specific basis.

If we consider how the average cost of technologies changed from 2010-16, we see that both solar PV (and to a lesser extent, solar thermal) dropped substantially. This cost reduction in solar PV has been dramatic over the past few decades, as shown in the chart. The price of solar PV modules has fallen more than 100-fold since 1976. On average, the technology has had a learning rate of 22 percent; this means that the cost falls by 22 percent for every doubling in solar PV capacity (although progress has not necessarily been constant over this period).

Levelised cost of electricity (LCOE) 2010 and 2016[9]



1976 2016

Average annual change Zoom to selection CHART DATA SOURCES

What are the safest sources of energy?

At the start of the Industrial Revolution, it was discovered that the energy in fossil fuels can be unlocked to make work more productive. This finding transformed human development: for most of history, living conditions across the world were equally poor. This began to change, rapidly, once we learnt how to use coal, oil, and gas. In more recent years, we have also gained access to modern renewables and nuclear power.

The increasing availability of cheap energy has been integral to the progress we've seen over the past few centuries. Energy access is one of the fundamental driving forces of development. The United Nations says that "energy is central to nearly every major challenge and opportunity the world faces today."

But energy production has downsides as well as benefits. There are three main categories:

- **Air pollution**: An estimated five million people die prematurely every year as a result of air pollution; fossil fuels and biomass burning are responsible for most of those deaths.

- **Accidents**: As well as deaths caused by the byproducts of energy production, people die in accidents in supply chains, whether in the mining of coal, uranium or rare metals; oil and gas extraction; the transport of raw materials and infrastructure; construction; or their deployment.
- **Greenhouse gas emissions**: Perhaps the most widely discussed downside is the greenhouse gases emitted by energy production, which are a key driver of climate change.

All energy sources have negative effects. But they differ enormously in the size of those effects. That difference can be easily summed up: by all metrics, fossil fuels are the dirtiest and most dangerous, while nuclear and modern renewable energy sources are vastly safer and cleaner.

From the perspectives of both human health and climate change, it matters less whether we use nuclear power or renewable energy, and more that we change to one or both of them rather than fossil fuels.

Nuclear power is far, far safer than fossil fuels, contrary to public belief

For most of the past 50 years, our energy systems have been dominated by fossil fuels, traditional biomass, hydropower and nuclear energy.[10]

In the future we expect renewable energy sources to contribute a rising share of total energy, but before we take a closer look at how renewables compare, let's first see how fossil fuels stack up against nuclear energy in terms of safety.

Anil Markandya and Paul Wilkinson (2007) published an analysis in the medical journal *The Lancet,* which compared the death rates from the major energy sources.[11] In this study they considered deaths from accidents, such as the Chernobyl nuclear disaster, occupational accidents in mining or power plant operations, and premature deaths from air pollution.[12]

This study was published in 2007, before the 2011 Fukushima Daiichi nuclear disaster in Japan. You might assume that the figures from this analysis therefore understate the death toll from nuclear energy, but in fact the opposite is true. Later in this article we look at a more recent study on the safety of low-carbon energy sources, published in 2016 which includes Fukushima impacts, and in fact reports a *lower* death rate than Markandya and Wilkinson (2007).[13] There were no direct deaths from the Fukushima Daiichi disaster. The official death toll was 573 people, all of which were premature deaths from evacuation and displacement of populations in the surrounding area.[14] In 2018, the Japanese government reported that one worker has since died from lung cancer as a result of exposure from the event.

To compare the safety of different energy sources, the researchers compared the number of deaths per unit of energy that is produced by them.[15] In the visualization we see the safety comparison of fossil fuels, nuclear and biomass, measured as the number of deaths per terawatt-hour of energy production. One terawatt-hour of energy is about the same as the annual energy consumption of 27,000 citizens in the European Union.[16]

Nuclear energy is by far the safest energy source in this comparison – it results in more than 442 times fewer deaths than the 'dirtiest' forms of coal; 330 times fewer than coal; 250 times less than oil; and 38 times fewer than gas. To be clear: the figures in this analysis was based on energy production in Europe where anti-pollution regulation and technologies are already well ahead of many countries in the world; in this case the death rate from fossil fuels may even be understated.

Let's put this into the context of the 27,000 Europeans that one terawatt-hour would provide for. Here we are taking a very simplistic example, but imagine we have a village of 27,000 people.[17] If they produced all of their energy from coal, we'd expect 25 people to die prematurely *every year* as a result (most from the impacts of air pollution). If they generated their energy from oil we'd expect 18 to die every year; and 3 to die if they relied on natural gas.

If they got their energy from nuclear power, in most years there would be no deaths. In fact, it would take at least 14 years before you would expect a single death. It may even be the case that this figure is an overestimate – later in the article we look at a more recent analysis of nuclear safety which suggests this is closer to one death every 100 years.

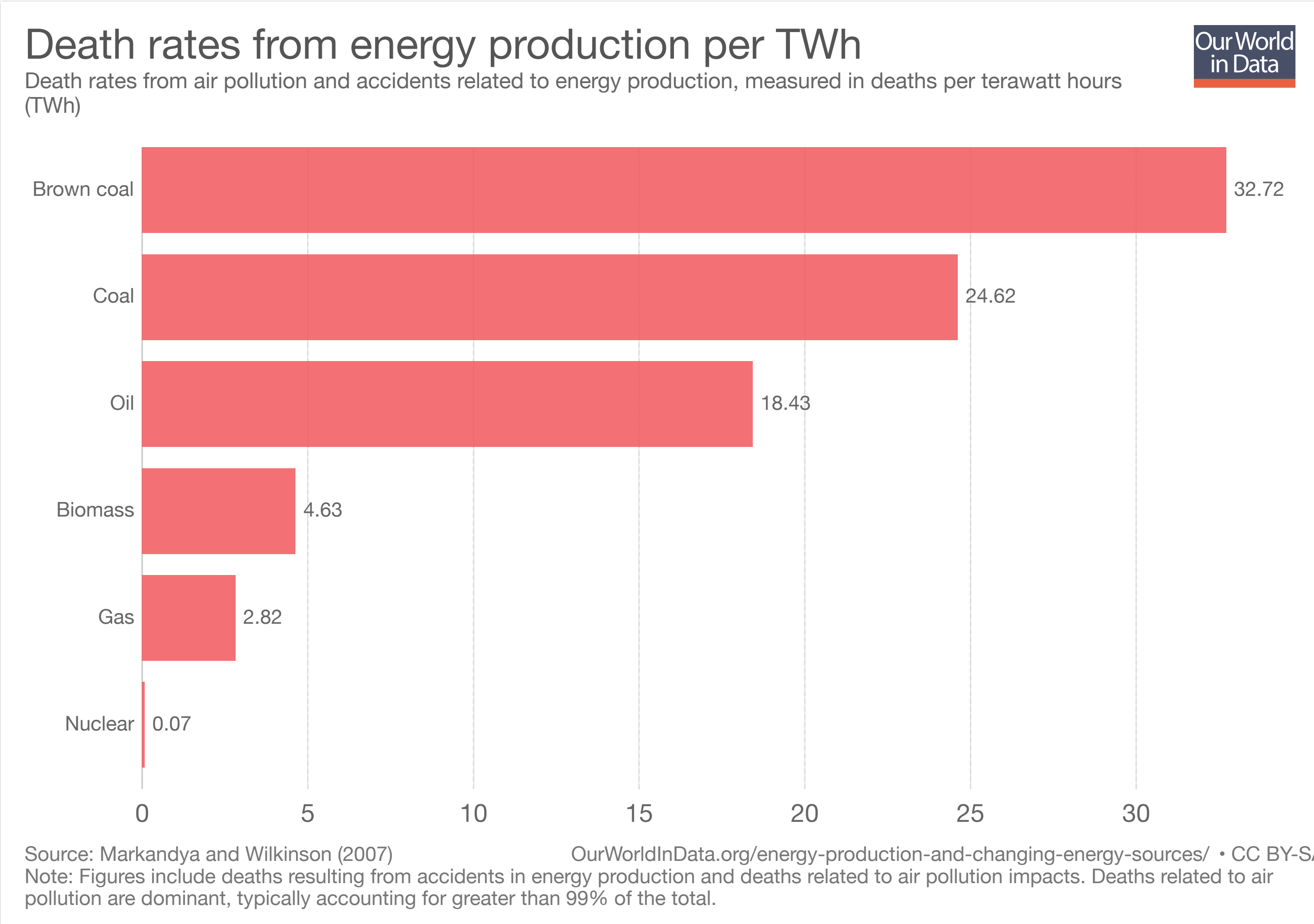
Fossil fuels have therefore killed many more people than nuclear energy.

In many countries, however, public opinion on nuclear energy is very negative and, as a consequence, policy decisions have in some places turned harshly against it.

In the wake of the 2011 Fukushima nuclear disaster, Germany announced plans to phase out nuclear power generation: over the period from 2011 to 2017 it shut down 10 of its 17 nuclear facilities, and plans to close the remaining reactors in 2022.[18]

These policy decisions can cost lives. In a study published in the journal *Environmental Science and Technology*, Pushker Kharecha and James Hansen (2013) reversed the conventional question of 'how many people have died from nuclear power?' into 'how many lives has nuclear power *saved*?'.[19] They analysed how many additional people would have died over the period from 1971 to 2009 if nuclear energy had been replaced by fossil fuels. The human cost would have depended on the mix of fossil fuels used to replace nuclear – more would have died if more coal was used than oil or gas – but they estimate an average figure of two million lives saved.[20]

Replacing nuclear energy with fossil fuels kills people. This is likely to be the case in the recent example of Germany. Most of Germany's energy deficit from scrapping nuclear was filled by increased coal production – the most polluting source with the largest health impacts. Analysis by Stephen Jarvis, Olivier Deschenes, and Akshaya Jha (2020) estimates that Germany's nuclear phase-out has come at the cost of more than 1,100 additional deaths each year as a result of air pollution.[21] Its plans to make its energy systems safer have done exactly the opposite.



Modern renewables are about as safe as nuclear energy

Renewable energy sources will in future make up an increasing share of energy supply. How does the safety of renewable energy compare?

Most of us have heard stories of hydropower dams flooding; people falling from roofs when installing solar panels; or wind turbines collapsing. And it's true, these events happen. But just how common are they? Are the safety concerns about renewable energy exaggerated?

Benjamin Sovacool and colleagues (2016) investigated the safety of low-carbon energy sources in a study published in the *Journal of Cleaner Production*.[22] In this analysis the authors compiled a database of as many energy accidents as possible over the period from 1950 to 2014 based on an extensive search of academic databases (including ScienceDirect and EBSCO host) and news reports via Google.[23] The full list of accidents is made available in the underlying study; in the results below the authors compare death rates over the period from 1990 to 2013 only.

In the visualization I have combined the two studies described above so we can compare fossil fuels, nuclear and renewable energy. Again, death rates are given per unit of energy to allow a comparison. If you want to compare *only* low-carbon energy sources, you can find this data here.

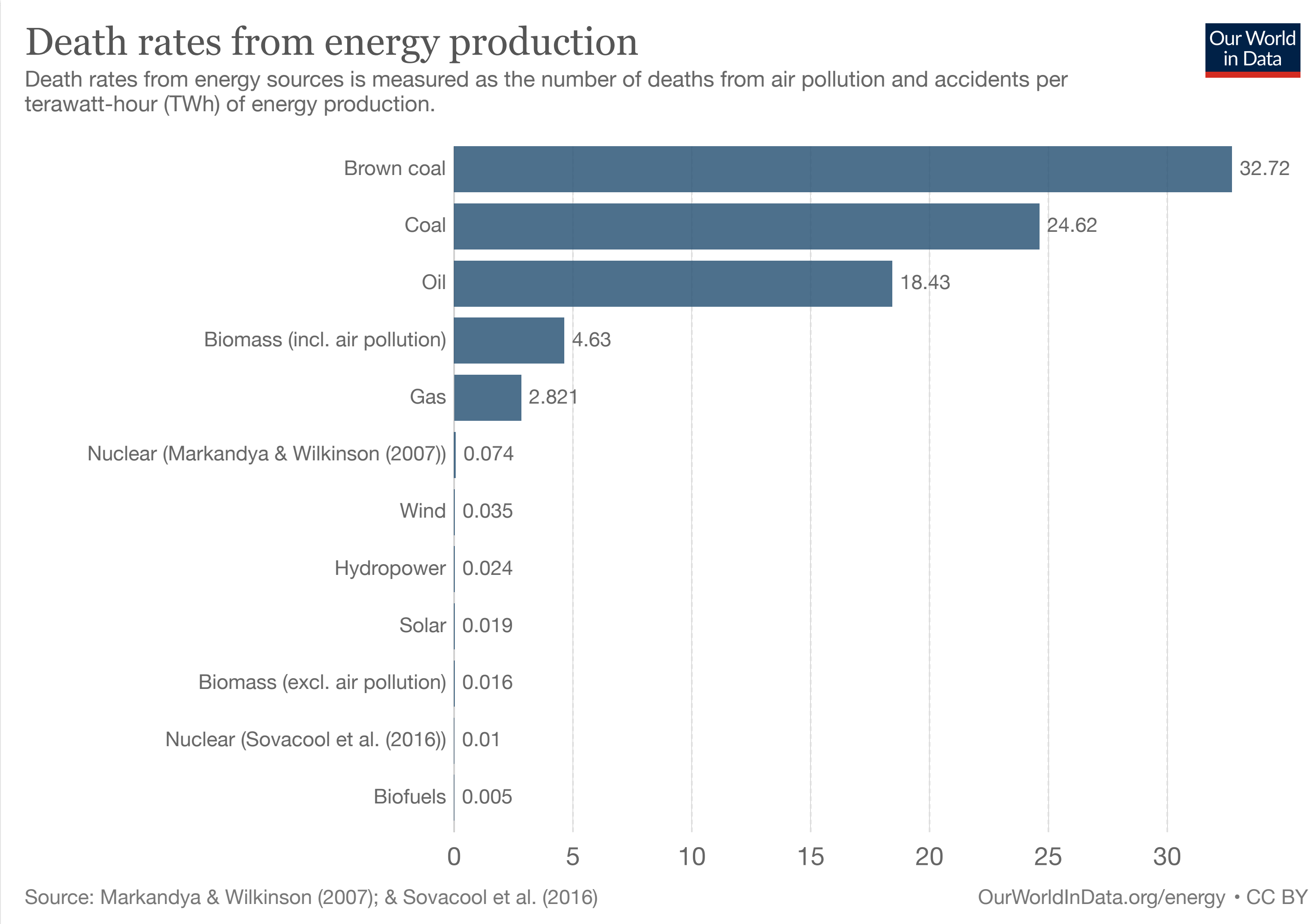
You will notice two values for both nuclear and biomass – these represent the slightly different estimates from the two different studies: the earlier work of Markandya and Wilkinson (2007) and recent analysis by Sovacool et al. (2016). I explain why these figures differ, and also how deaths from nuclear energy are estimated in the dropdown box at the end of this post.

We see a massive difference in death rates from fossil fuels versus nuclear and modern renewable technologies. Nuclear and renewable sources are similarly safe: in the range of 0.005 to 0.07 deaths per TWh. Both nuclear and renewable energy sources have death rates hundreds of times lower than coal and oil, and are tens to hundreds of times safer than gas.

This conclusion holds true regardless of whether you choose the higher (conservative) or lower death rate for nuclear energy. It is comparable to renewable energy technologies in both cases.

Let's again put this into the context of our town of 27,000 EU citizens, who would collectively consume around one terawatt-hour of energy a year. These are the impacts if they got all of their energy from a given source:

- **Coal**: 25 people would die prematurely every year;
- **Oil**: 18 people would die prematurely every year;
- **Gas**: 3 people would die prematurely every year;
- **Nuclear:** it would take between 14 and 100 years before someone died;
- **Wind**: 29 years before someone died;
- **Hydropower or solar:** 42 years before someone died;
- **Solar:** 53 years before someone died.



As well as being safe, modern renewables and nuclear energy are both extremely low-carbon

So far we've only considered the short-term health and social impacts of these energy sources. But we should also take into consideration their potential for future, longer-term impacts in their contribution to climate change.

The good news is that the safest sources are those which are low-carbon.

In the visualization I have plotted the death rates per unit energy data we looked at previously (on the y-axis) versus each source's greenhouse gas emissions per energy unit (on the x-axis).

This measure of greenhouse gas emissions considers the total carbon footprint over the full lifecycle; figures for renewable technologies, for example, take into consideration the footprint of the raw materials, transport and their construction. I have adopted these figures as reported in the IPCC's 5th Assessment Report (AR5), and more recent life-cycle figures by Pehl et al. (2017) which look at the emissions intensities of technologies in '2°C-compatible' energy transitions to 2050.[24,25,26]

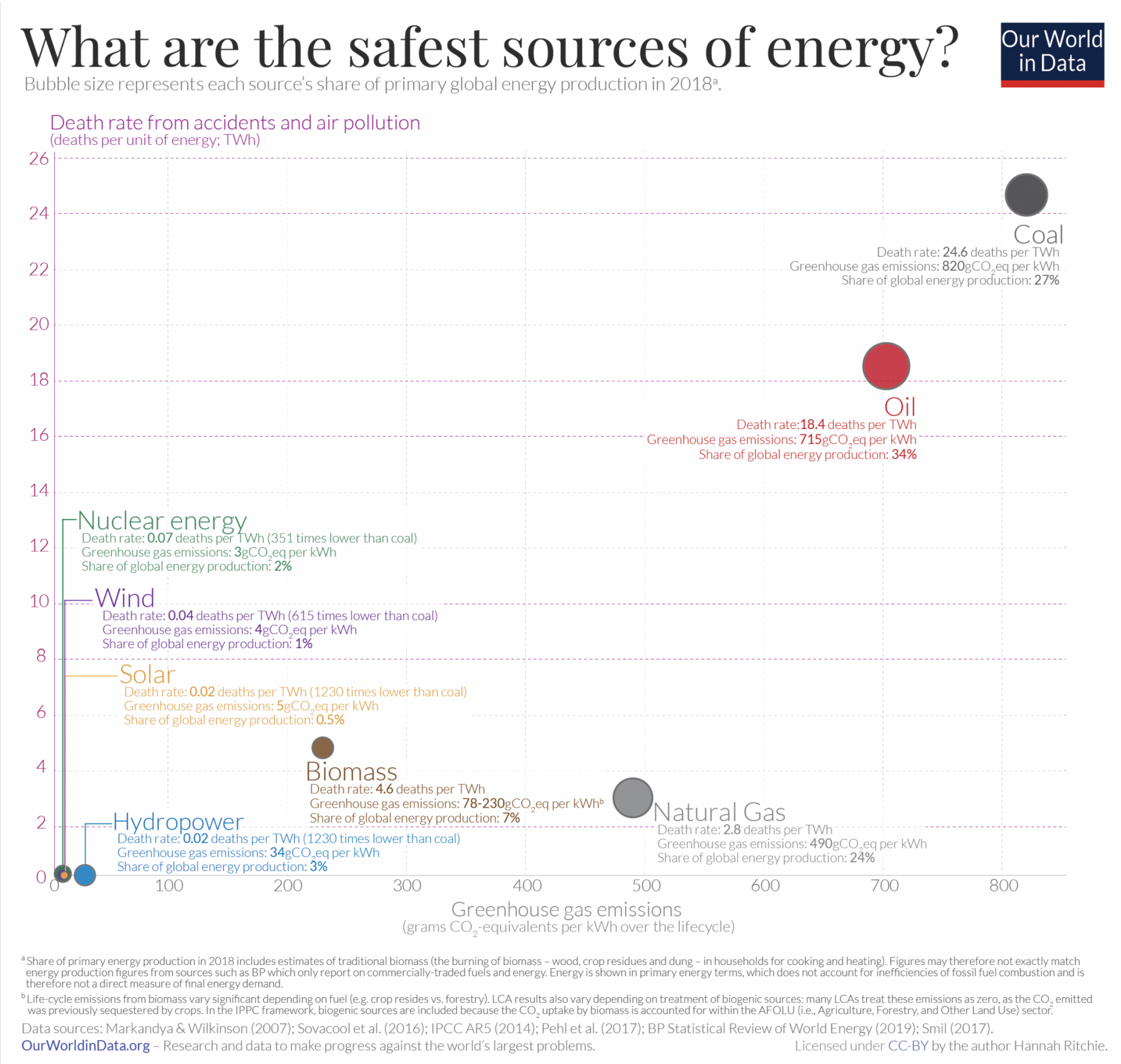
The size of each bubble represents its share of global primary energy production in 2018 (including traditional biomass in the total).[27]

There are few trade-offs here – the safer energy sources are also the least polluting. Coal performs poorly on both metrics: it has severe health costs in the form of air pollution, and emits large quantities of greenhouse gas emissions per unit of energy. Oil, then gas, are better than coal, but are still much worse than nuclear and renewables on both counts.

Nuclear, wind, hydropower and solar energy all cluster in the bottom-left of the chart. They are all safe, low-carbon options. But they still account for a very small share of global energy consumption – less than 10% of primary energy – as we see from the bubble size.

There is fierce debate about which low-carbon energy technologies we should pursue. And there are of course other aspects to consider, such as cost, construction times, and location-specific resource availability. But on the basis of human health, safety and carbon footprint, nuclear and modern renewables are both winners. A number of studies have found the same: there are large co-benefits for human health and safety in transitioning away from fossil fuels, regardless of whether you replace them with nuclear or renewables.[28]

Fossil fuels are killing millions of people every year, and endanger many more from the future risks of climate change. We must shift away from them, drawing on all of our available options to do so.



Why do biomass and nuclear estimates vary? How are nuclear deaths calculated?

The analysis of Markandya and Wilkinson (2007) and Sovacool et al. (2016) report different death rates for biomass and nuclear. Why do these estimates vary?

Biomass: The difference between the biomass death rate figures is simple to explain: Markandya & Wilkinson include the health impacts of air pollution. Indoor air pollution, which results from the burning of solid fuels (including wood, dung and other biomass sources) for cooking and heating in households kills 1.6 million people every year, mainly in lower-income countries. Markandya & Wilkinson (2007) focus their analysis in Europe where biomass energy is produced in state-of-the-art (in the year 2007, at least) facilities that maintain EU environmental standards. These health impacts are much lower than for indoor air pollution typical of lower-income countries, but can still be a significant contributor to outdoor air pollution. The inclusion of air pollution deaths is why their estimated death rates are much higher.

In contrast, Sovacool et al. (2016) do not include air pollution estimates, and instead focus on deaths from accidents at biomass production facilities (such as explosions or fires) and their supply chains. As a result, total death rate figures are much lower.

Nuclear: there are two key points to differentiate in the estimates of nuclear energy safety. The first is the period which the studies cover. Analysis by Markandya & Wilkinson (2007) predates the 2011 Fukushima nuclear disaster in Japan, and therefore does not include this accident in its estimates. This fact, however, does not fully explain why the two studies differ: we might assume the inclusion of the Fukushima disaster would increase death rates but in fact the estimates of Sovacool et al. (2016) are *lower*.

The largest differentiator here is the period which the Sovacool et al. (2016) estimates cover. They report normalized death rates over the limited period from 1990 to 2013. This means the 1986 Chernobyl accident was not included. Sovacool et al. (2016) only include deaths from the Fukushima accident, with 573 attributed deaths. It is useful to note here that not all deaths were a direct result of the accident: for Fukushima, there were no direct deaths from the disaster; one confirmed death from radiation exposure; and the rest noted as premature deaths from evacuation and displacement of populations in the surrounding area.[29]

The deaths which occurred as a result of the nuclear disaster were the result of the *response* to the event, rather than the event itself.

Markandya and Wilkinson (2007) include estimated death tolls from distinct accidents (not including Fukushima) but also provide an estimate of deaths from occupational effects. They note that deaths:
"*can arise from occupational effects (especially from mining), routine radiation during generation, decommissioning, reprocessing, low-level waste disposal, high-level waste disposal, and accidents. The data […] show occupational deaths of around 0·019 per TWh,* ***largely at the mining, milling, and generation stages****. These numbers are small in the context of normal operations. For example, a normal reactor of the kind in operation in France would produce 5·7 TWh a year. Hence, more than 10 years of operations would be needed before a single occupational death could be attributed to the plant. Likewise, numbers of deaths through cancer, severe hereditary effects, and non-fatal cancers caused by normal operations are extremely small."*

The estimates of Markandya and Wilkinson (2007) are therefore higher than Sovacool et al. (2016) because they include the Chernobyl disaster, and assume additional occupational deaths at various stages of the nuclear supply chain. This methodology adopts the 'linear non-threshold' (LNT) method, which assumes there is no minimum 'safe' threshold of radiation exposure, and that cancer risk increases linearly from zero. Since the study's publication, the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has made clear that the LNT method represents a highly cautious approach, and likely overstates the number of potential cancer cases and deaths which result from low-level radiation exposure.[30]

These estimates are therefore likely to be highly conservative. The LNT method, is however, still typically adopted in the development of radiation protection.

If we look at the case of the 2011 Fukushima disaster: the World Health Organization (WHO) Report published five years on, suggests very low risk of increased cancer deaths in Japan.[31] In a review of the response and long-term health impacts of Fukushima, published by Michael Reich and Aya Goto in *The Lancet*, the authors note that: "no one has died from radiation exposure, and the UN Scientific Committee on the Effects of Atomic Radiation report in 2013 stated that substantial changes in future cancer statistics attributed to radiation exposure are not expected to be observed".[32,33] These findings highlight the shift of consensus away from the historical linear non-threshold method, where it was assumed that even very low levels of exposure increased cancer risk.

Data Sources

IN THIS SECTION

Long run

The History Database of the Global Environment (HYDE)

- **Geographical coverage:** Global – by world region
- **Time span:** Since 1800
- **Available data:**
  - *'Total final energy consumption*' since 1800 by world region
  - *'Total global Energy consumption'* per fuel type & by world region

Correlates of War

- **Data:** 'Primary Energy Consumption' (thousands of Metric-ton Coal Equivalent)
- **Geographical coverage:** Global – by country
- **Time span:** 1816-2007
- **Available at:** Online at www.correlatesofwar.org

- *The original data source for data after 1970 is the United Nations' Energy Statistics Database UNESD. Data for the time before 1970 is taken from Mitchell International Historical Statistics. See the codebook on page 61.*

The Shift Project (TSP)

- **Data:** Historical Energy Consumption Statistics and Historical Energy Production Statistics
- **Geographical coverage:** Global – by country and world region
- **Time span:** Since 1900
- **Available at:** Both datasets are online at https://www.theshiftdataportal.org/.

Post 1950

IEA – International Energy Agency

- **Data:** Data on electricity, oil, gas, coal and renewables. Data on CO2 emissions (also projections)
- **Geographical coverage:** Global – by country
- **Time span:** Last decades
- **Available at:** Online at www.iea.org
- *The IEA is publishing the World Energy Outlook.*
- *You have to pay to access the IEA databases. But some data is available through Gapminder, for example Residential Energy Use (%). (for few countries since 1960, for more countries since 1971 or 1981)*

Energy Information Administration

- **Data:** Total and crude oil production, oil consumption, natural gas production and consumption, coal production and consumption, electricity generation and consumption, primary energy, energy intensity, CO2 emissions and imports and exports for all fuels
- **Geographical coverage:** Global – by country
- **Time span:** Annual data since 1980
- **Available at:** Online at ww.eia.gov
- *EIA is a US government agency.*

BP Statistical Review of World Energy

- **Data:** BP publishes data on Oil, Gas Coal, Nuclear Energy, Hydroelectricity, Renewables, Primary Energy Consumption, Electricity Generation, Carbon Dioxide Emissions
- **Geographical coverage:** Global – by country and region

- **Time span:** Annual data since 1951
- **Available at:** Online at www.BP.com

World Development Indicators – World Bank

- **Geographical coverage:** Global – by country and world region
- **Time span:** Last decades
- **Data:** Energy use (kt of oil equivalent) – Energy use (kg of oil equivalent *per capita*) – Energy production (kt of oil equivalent)
- *Many more related indicators.*

Eurostat

- **Data:** Production & consumption of energy.
- **Geographical coverage:** Europe
- **Time span:**
- **Data on:** Energy production and imports – Consumption of energy – Electricity production, consumption and markets.

References

1. Ben Gales, Astrid Kander, Paolo Malanima and Mar Rubio (2007) – North versus South: Energy transition and energy intensity in Europe over 200 years. European Review of Economic History Vol. 11, No. 2 (August 2007), pp. 219-253. Cambridge University Press DOI: http://dx.doi.org/10.1017/S1361491607001967. Online here.
2. These commitments were made based on the submission of so-called "intended nationally determined contributions" (INDCs), whereby countries submitted their long-term targets for climate change mitigation. These targets can be explored and tracked at the World Resource Institute's CAIT Climate Data Explorer. Available online.
3. Arguably, the potential for the electrification of many aspects of our transport system (for example, the rise in electric vehicles) means that decarbonisation of our electricity grid will become increasingly important
4. These commitments were made based on the submission of so-called "intended nationally determined contributions" (INDCs), whereby countries submitted their long-term targets for climate change mitigation. These targets can be explored and tracked at the World Resource Institute's CAIT Climate Data Explorer. Available online.
5. Chontanawat, J., Hunt, L. C., & Pierse, R. (2008). Does energy consumption cause economic growth?: Evidence from a systematic study of over 100 countries. *Journal of Policy Modeling*, *30*(2), 209-220. Available online.
6. Chontanawat, J., Hunt, L. C., & Pierse, R. (2008). Does energy consumption cause economic growth?: Evidence from a systematic study of over 100 countries. *Journal of Policy Modeling*, *30*(2), 209-220. Available online.
7. Akinlo, A. E. (2008). Energy consumption and economic growth: Evidence from 11 Sub-Sahara African countries. *energy economics*, *30*(5),

2391-2400. Available online.

8. You can also view this chart interactively.

9. IRENA (2017), REthinking Energy 2017: Accelerating the global energy transformation. International Renewable Energy Agency, Abu Dhabi. Available online.

10. There are numerous conditions under which biomass can be used as an energy source. Here when we refer to 'traditional biomass' we mean the burning of solid fuels – wood, crop residues, dung – in households for cooking and heating. This is common in low-to-middle income countries which don't have access to 'clean fuels' for cooking. The use of traditional biomass results in high levels of indoor air pollution, which kills 1.6 million people every year.

    'Traditional biomass' is distinct from modern biomass, which is the burning of wood and biomass waste in industrial facilities.

11. Markandya, A., & Wilkinson, P. (2007). Electricity generation and health. *The Lancet*, 370(9591), 979-990.

12. In all cases, pollution-related deaths dominate. In the case of brown coal, coal, oil and gas, they account for greater than 99% of deaths; 100% of biomass-related deaths; and 70% of nuclear-related deaths (where radiation here is classified under pollution).

13. Sovacool, B. K., Andersen, R., Sorensen, S., Sorensen, K., Tienda, V., Vainorius, A., … & Bjørn-Thygesen, F. (2016). Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems. *Journal of Cleaner Production*, 112, 3952-3965.

14. The Yomiuri Shimbun, 573 deaths 'related to nuclear crisis', The Yomiuri Shimbun, 5 February 2012, http://www.yomiuri.co.jp/dy/national/T120204003191.htm.

15. Coal, oil, gas, nuclear and biomass produce very different quantities of energy. We cannot simply compare them on this basis: we'd expect that the largest sources of energy would then have the greatest impacts. To do a fair comparison we have to look at the impacts of producing *one unit* of energy from each of the sources, then compare.

16. The average per capita energy consumption in the EU in 2015 was 37,298 kilowatt-hours (kWh). One terawatt-hour (which is equivalent to 1 billion kWh) is therefore the annual energy consumption of [1×10^9 kWh / 37,298 = 26,811 EU citizens].

17. There are of course a range of additional factors which makes this thought experiment simplistic: the number of deaths could depend on factors such as the proximity of residents to the power plant, the age of profile of the population.

18. Jarvis, S., Deschenes, O., & Jha, A. (2019). The Private and External Costs of Germany's Nuclear Phase-Out (No. w26598). *National Bureau of Economic Research*.

19. Kharecha, P. A., & Hansen, J. E. (2013). Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. *Environmental Science & Technology*, 47(9), 4889-4895.

20. van der Merwe, A. (2019). Nuclear energy saves lives. *Nature*, 570(7759), 36.

21. Jarvis, S., Deschenes, O., & Jha, A. (2019). The Private and External Costs of Germany's Nuclear Phase-Out (No. w26598). *National Bureau of Economic Research*.

22. Sovacool, B. K., Andersen, R., Sorensen, S., Sorensen, K., Tienda, V., Vainorius, A., … & Bjørn-Thygesen, F. (2016). Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems. *Journal of Cleaner Production*, 112, 3952-3965.

23. The definition of 'low-carbon' is sometimes contested: the authors in this study use it to collectively describe eight energy systems: biofuels; biomass; geothermal electricity; hydroelectricity; hydrogen; nuclear power; solar energy (including solar PV as well as solar thermal or Concentrated Solar Power); and wind power (onshore and offshore).

    They define an accident as: "an unintentional incident or event at an energy facility that led to either one death (or more) or at least $50,000 in

property damage," which is consistent with definitions in the research literature.

Sovacool, B. K., Kryman, M., & Laine, E. (2015). Profiling technological failure and disaster in the energy sector: A comparative analysis of historical energy accidents. *Energy*, 90, 2016-2027.

Since air pollution from low-carbon energy is negligible (traditional biomass is the exception here), most of the deaths from these sources relate to accidents.

24. Schlömer S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, and R. Wiser, 2014: Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

25. The IPCC AR5 report was published in 2014, and relies on studies conducted several years prior to its publication. For technologies which have been developing rapidly – namely solar, wind and other renewables, production technologies and intensities have changed significantly since then, and will continue to change as energy systems decarbonize. Life-cycle figures for nuclear, solar, wind and hydropower have therefore been adopted by the more recent publication by Pehl et al. (2017), published in *Nature Energy*.

    Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E. G., & Luderer, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, *2*(12), 939-945.

    The Carbon Brief provides a clear discussion of the significance of these more recent lifecycle analyses in detail **here**.

26. Since oil is conventionally not used for electricity production, it is not included in the IPCC's reported figures per kilowatt-hour. Figures for oil have therefore been taken from Turconi et al. (2013). It reports emissions in kilograms of CO_2eq per megawatt-hour. Emissions factors for all other technologies are consistent with results from the IPCC. The range it gives for oil is 530–900: I have here taken the midpoint estimate (715 kgCO_2eq/MWh, which is also 715 gCO_2eq/kWh).

    Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews*, 28, 555-565.

27. Energy data here is presented in primary energy terms. This means it does not take into account the inefficiencies in the conversion of fossil fuel energy inputs to final energy consumption. Since we are concerned here with the health impacts and greenhouse gas emissions generated by energy production (i.e. energy inputs) this is a more appropriate comparison than final energy demand – final energy demand would underestimate the air pollution and GHGs generated from fossil fuels. Energy comparisons by primary energy consumption and 'corrections' which are a better approximation of final energy demand can be explored here.

28. Burgherr, P., & Hirschberg, S. (2014). Comparative risk assessment of severe accidents in the energy sector. *Energy Policy*, 74, S45-S56.

    McCombie, C., & Jefferson, M. (2016). Renewable and nuclear electricity: Comparison of environmental impacts. *Energy Policy*, 96, 758-769.

    Hirschberg, S., Bauer, C., Burgherr, P., Cazzoli, E., Heck, T., Spada, M., & Treyer, K. (2016). Health effects of technologies for power generation: Contributions from normal operation, severe accidents and terrorist threat. *Reliability Engineering & System Safety*, 145, 373-387.

    Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., … & Mima, S. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, 10(1), 1-13.

    Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., … & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences*, 112(20), 6277-6282.

29. The Yomiuri Shimbun, 573 deaths 'related to nuclear crisis', The Yomiuri Shimbun, 5 February 2012, http://www.yomiuri.co.jp/dy/national/T120204003191.htm.

30. UNSCEAR. Sources and Effects of Ionizing Radiation. Volume II: Effects. Scientific Annexes C, D and E. UNSCEAR 2008 Report. United Nations Scientific Committee on the Effects of Atomic Radiation. United Nations sales publication E.11.IX.3. United Nations, New York, 2011.

31. World Health Organization (2016). FAQs: Fukushima Five Years On. Available online at: https://www.who.int/ionizing_radiation/a_e/fukushima/faqs-fukushima/en/.

32. Reich, M. R., & Goto, A. (2015). Towards long-term responses in Fukushima. *The Lancet*, 386(9992), 498-500.

33. United Nations Scientific Committee on the Effects of Atomic Radiation. (2015). Report of the United Nations Scientific Committee on the effects of atomic radiation to the general assembly.

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